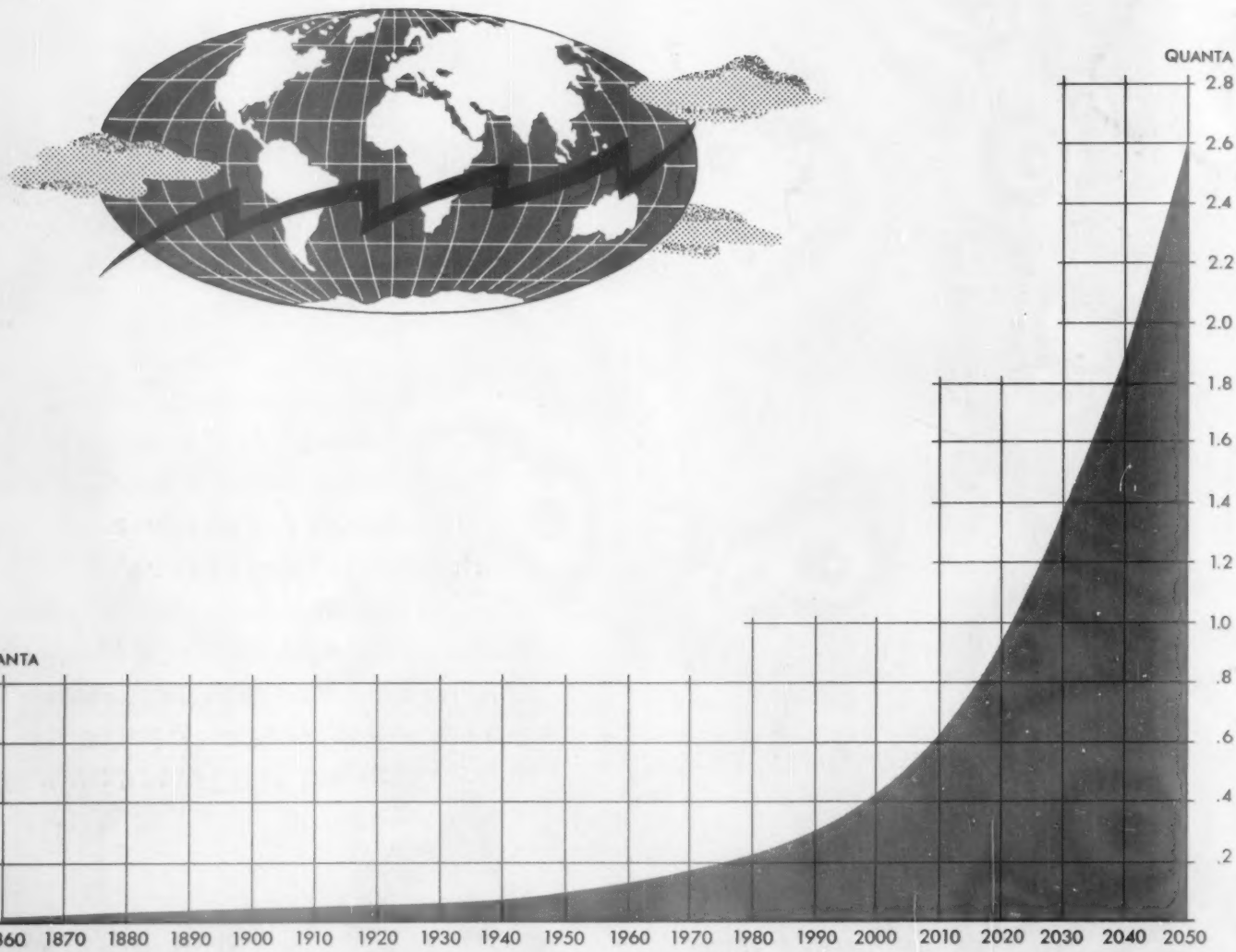
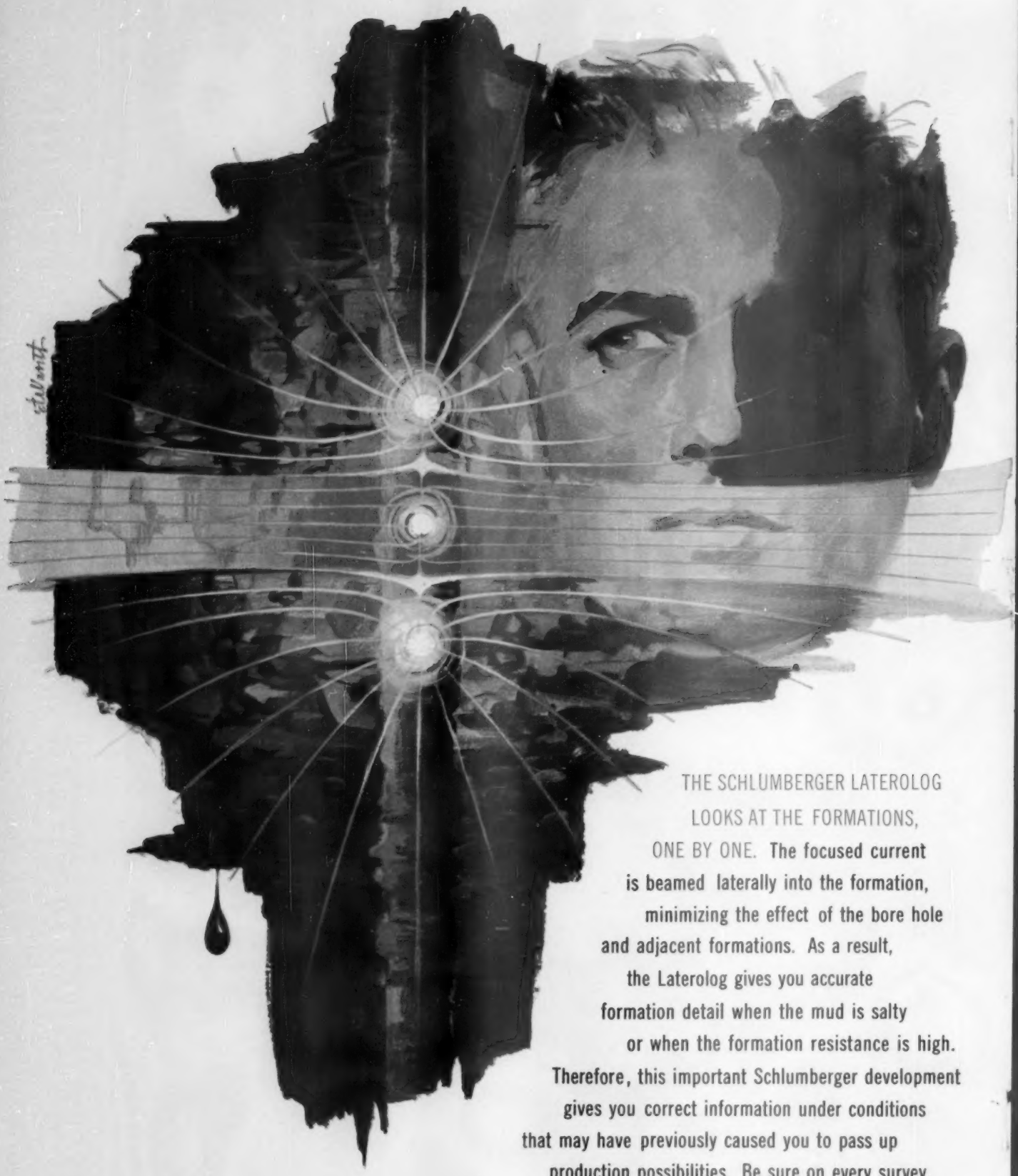
MARCH 1955

JOURNAL OF PETROLEUM TECHNOLOGY



TOTAL WORLD ENERGY INPUT • 1860-2050



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On the Cover: The illustration introduces discussions concerning the future demand for energy in the world presented in this issue by two papers: "The Economics of the International Petroleum Industry," pages 9-13, and "Some Sidelights in Petroleum's Economic Progress," pages 14-18.

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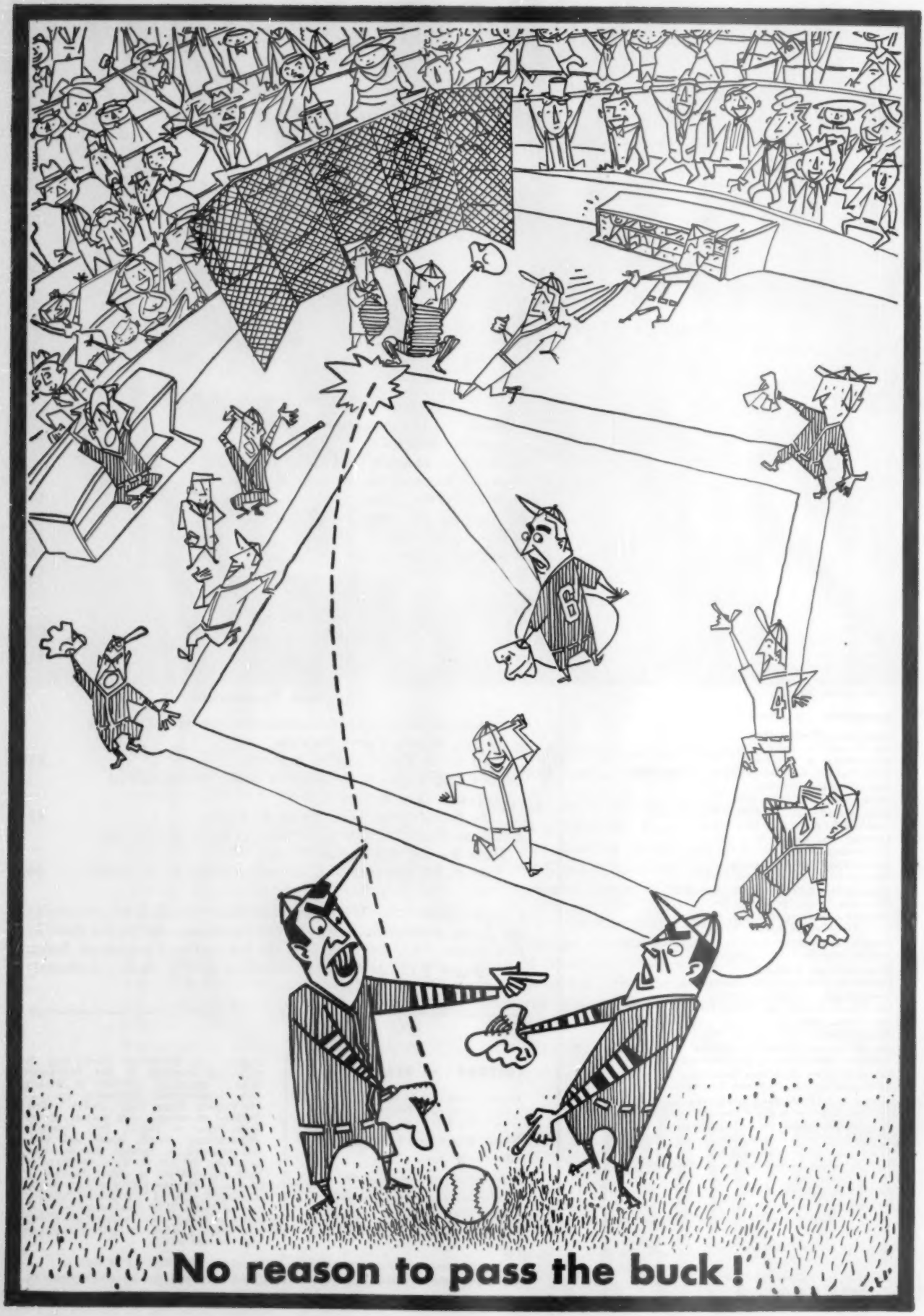
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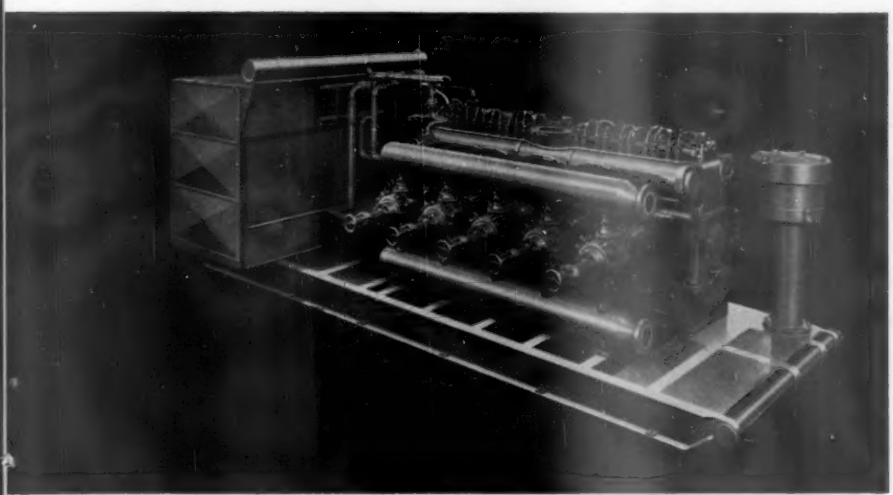

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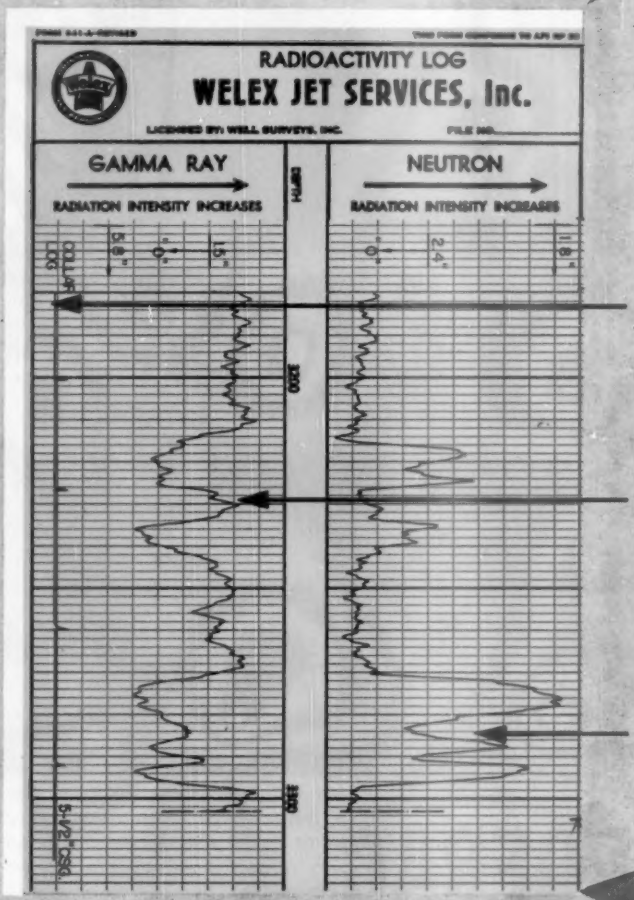

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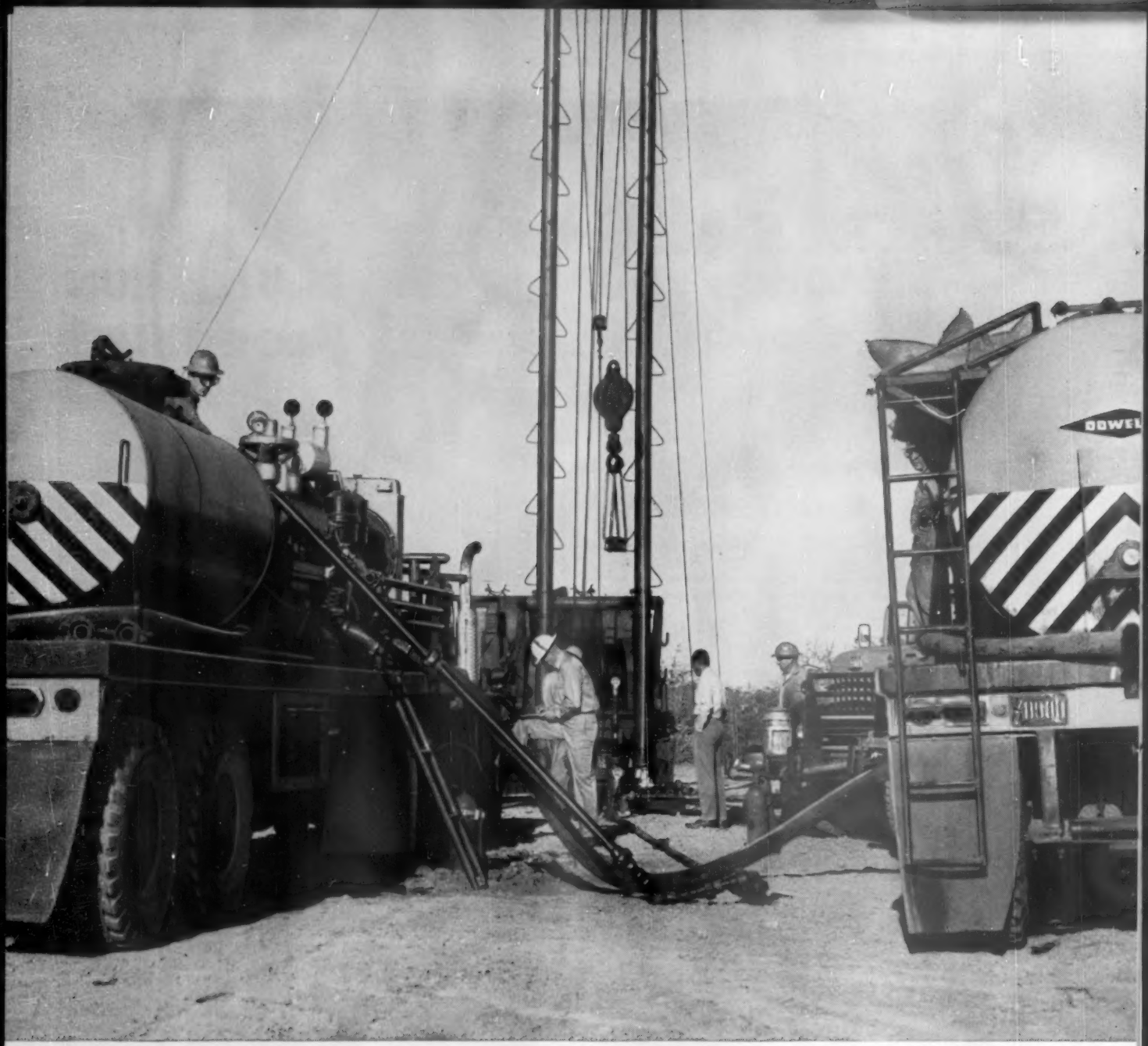

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FEATURE ARTICLE

THE ECONOMICS of the INTERNATIONAL PETROLEUM INDUSTRY

A. H. CHAPMAN
JAMES TERRY DUCE
MEMBERS AIME

ARABIAN AMERICAN OIL CO.
WASHINGTON, D. C.

Introduction

The petroleum industry's operations not only affect the lives of all of us here, but also play a major role in shaping the economy and influencing the political life of every nation in the world. We find ourselves today face-to-face with enormous responsibilities at home and abroad. In this paper the writers will review some of the dangers and pitfalls which the industry has overcome in the past, and, even more important, take a good look at the future — particularly the long term future of supply and demand, and the political factors which underlie them.

Thirty-five years ago we were gravely concerned over our vanishing oil resources. At that time one of the pundits of the economic world recommended to his friends that they sell their oil stocks for the reason that the industry would soon have no raw material with which to work. At the same time, a Kansas professor strongly advised against "senseless joy-riding," as he considered it a waste of precious natural resource which, in his opinion, should only be sold at a very high price as, of course, a measure of conservation. However, our Kansas professor felt also that the way to keep the price high was for the states to siphon-off the profits in high taxes, and he mentioned taxes of a dollar a barrel.

Our first and greatest concern then was the scarcity of the basic raw material upon which the industry lived. Eugene Stebinger, then chief geologist of the U. S. Geological Survey, had estimated the possible world reserves at under 30 billion bbl. Mid-Continent crude sold for over $3/bbl. Since that time we have consumed some 50 billion bbl and today our forward supply picture has never been more promising.

In the time that has intervened the American public has often been fearful that our domestic supplies of crude oil would run out. Sometimes they have been frightened by the statistics of the economists, who have quoted proved reserves in terms of years supply, such as, for example, the statement that reserves in the U. S. today represent a supply for some 13 years. The public failed to realize that this type of statistic is merely a yardstick and that the industry has geared itself through the years to a rate of production and discovery balanced against the market. This relationship is most simply expressed in these terms: when the ratio falls, exploration must be accelerated; when it rises, we can slow down.

Ever-Increasing Demand

The industry, however, has weathered all storms and finds itself today at a point where improved technology has found oil sufficient for current needs, and where supplies for the immediate future are abundant in spite of the rapidly growing demand — particularly those supplies known to exist in areas outside of the United States. On the other hand, the amount of oil required today by our constantly growing machine age would have seemed incredible in 1918.

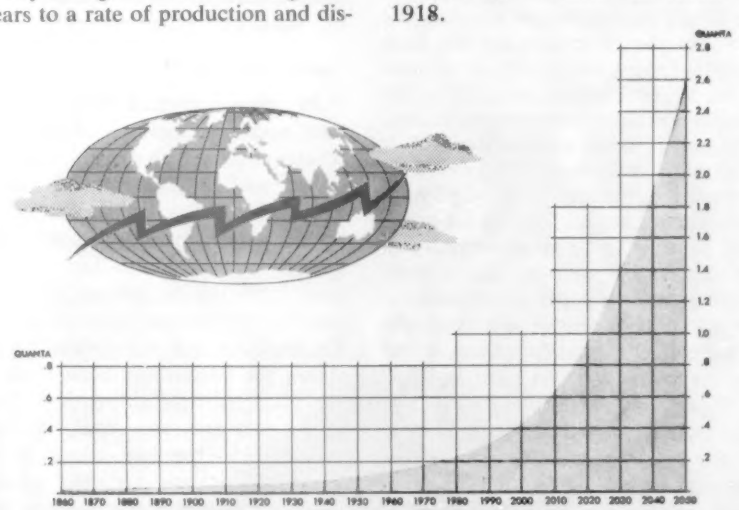

Fig. 1 — Total World Energy Input, 1860-2050.
Based on Putnam's 3 per cent curve for total world.
Based on the following conditions:

1. **5 billion population in 2050.**
2. **3 per cent per capita annual growth in demand for energy.**

Paper presented at Petroleum Branch Fall Meeting in San Antonio, Oct. 17-20, 1954.

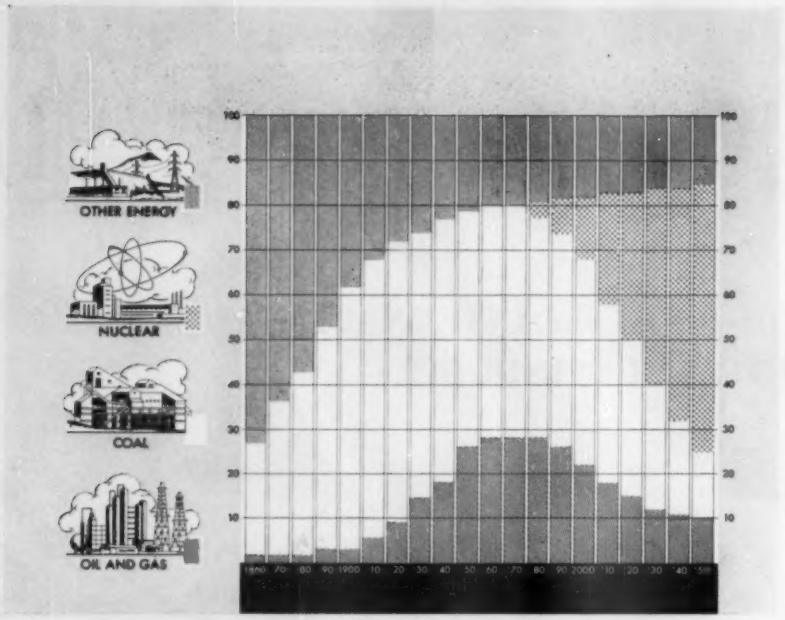

Fig. 2 — Per Cent of Total World Energy Input 1860-2050.

The most important factor in the industry today is this growing demand, a never-ceasing technological wonder. Fortunately, there have been made available to us two intriguing analyses of the future demands. One of these is the report of the Paley Commission[1] and the other is the much broader report contained in the volume, *Energy in the Future*, by Palmer Putnam[2], the result of a comprehensive study made for the Atomic Energy Commission.

The Putnam Report

It might be interesting therefore to take Putnam's report covering the possible use of energy for the next hundred years and dissect it to show what his conclusions mean as to the future requirements for petroleum. His energy study commences with a searching analysis of the growth of population. Several rates of population growth are set forth in his book, and in order to be as conservative as possible, the authors have used throughout this paper a compounded growth rate which will approximately double the population of the world by the year 2050 and have assumed a 3 per cent annual increase in the per capita demand for energy.[3] This is the lowest of the estimates which Putnam makes and is, therefore, the most conservative possible interpretation that can be put upon his calculations.

Fig. 1, based on his figures, sets forth the predicted total annual energy input of the world for the period 1860 to 2050. In this figure we have employed Putnam's interesting unit for energy which he calls a "Quantum." The Quantum consists of 10^{15} Btu's, and it is the equivalent of 38 billion tons of bituminous coal or 168 billion bbl of oil. Fig. 1 indicates that the total energy input for the 100-year period would be 80 Quanta, and that it would be running at the rate of 2.6 Quanta per annum by 2050. Note that this includes all economic requirements for energy — oil, coal, and other energy sources.

Nuclear Fuel in 1970

In another part of his study Putnam makes an analysis of the types of energy which the world has used in the past to satisfy this demand.[4] This analysis has been extrapolated by the writers, using other data presented by Putnam, to carry to the year 2050 the percentage contribution by the various types of energy. To illustrate this calculation, Fig. 2 shows the percentage annual use of the four principal categories of energy — oil and gas, coal, nuclear, and other — the last consisting of wood, vegetable growth, animal power, wind power and water power, etc. On this figure, you will note, Putnam predicts that the use of nuclear fuel will begin to carry a measurable amount of the energy load in the year 1970. Also, it is calculated that at about this time oil and gas will have achieved its maximum percentage usage, namely 27 per cent of the total world energy requirements. However, by the year 2050 oil and gas will have been reduced to 10 per cent of the total load, coal to 15 per cent and nuclear energy will increase to 60 per cent. Quantitively the 27 per cent of the 1970 requirements represents a far smaller quantity than the 10 per cent of the predicted requirements for 2050 — the predicted requirement in 1970 being 20,500,000 B/D, and that in 2050 being 120 million B/D (oil and gas equivalent).

Future Oil and Gas Production

If the foregoing information is equated into terms of oil and gas required, they will be as indicated in Fig. 3, in which predicted annual oil and gas production is plotted for the period 1860 to 2050. Note that in the latter year the requirements of the world would be at the rate of 44 billion bbl per year, or 120 million B/D production of oil/gas equivalent. If this conclusion is within shooting distance of correct, it can be matched against the most optimistic estimate made in recent years with respect to reserves of oil and gas, shale oil, and tar sands.

The world consumed 98 billion bbl of oil/gas equivalent between the years 1860 to 1953. At the end of 1953 published estimates of the proven reserves of gas and oil amounted to the equivalent of 188 billion bbl of oil.* If no additional oil or gas were discovered from 1953 onward, these 188 billion barrel reserves would carry us theoretically to the year 1980. However, our geologists tell us that they believe that other more important quantities of oil will be discovered and also that at this point we must take into consideration the reserves in the tar sands and shales producible at some price. Putnam uses twice the 1950 costs of production as limiting recoverable reserves. The authors, therefore, list below the total hydrocarbon resources which Putnam cites on the authority of the studies of others.

It is probable that both the tar sand and shale reserve figures are vast under-estimates. Too little of them is known to be sure at present.

[1]References given at end of paper.

*Oil 66 per cent and gas 34 per cent, see Table 1.

TABLE 1 — ESTIMATES PROBABLE HYDROCARBON FUELS, SHALE, AND TAR SANDS AND UNDISCOVERED OIL AND GAS

Item	Quantity in Billions of Barrels Oil or Equivalent
Crude Oil (*Lewis Weeks* plus 50 per cent)[5]	730
Gas (34 per cent of undiscovered oil)	250 (based on relative Btu content)
Tar Sands	300
Shale Oil	200
Total	1,480

Supplies Exhausted in 2041

The 188-billion bbl of reserves indicated to exist at the end of 1953 are, of course, included in the total of 1,480 billion bbl of possible world hydrocarbon reserves listed in Table 1. Since the 188 billion bbl are going to carry us to the year 1980, then there may be 1,292 billion bbl of possible hydrocarbon reserves existing in the world at the end of 1980. Again it must be emphasized that some of these figures are under-estimates. Projecting this quantity onto our production curve, Fig. 3, we find that all of these estimated reserves would be completely used up in the year 2041, and there will be a deficit between the years 2041 and 2050 of 348 billion bbl. In other words, if the Putnam calculations are correct, 2041 is the year in which all the world's hydrocarbons recoverable at twice 1950 costs will be used up.

Gas has been handled in these calculations on the basis of Putnam's estimate that an average of 3,000 cu ft of gas should be produced for every barrel of oil.[6] If, then, oil and gas are grouped together, the gas hydrocarbons on a Btu basis contribute 34 per cent of the energy and oil contributes 66 per cent. Since the Putnam calculations reveal that the demand for fuels is rising so fast and that hydrocarbon reserves are limited, the conclusion that should follow is that the best scientific processes should be applied to the utilization of gas reserves so that they may make their full contribution to the world's demands for energy.

All of the above should probably be classified as merely a mental exercise; however, it contains an important lesson, which is the clear indication that the future demand for hydrocarbons is likely to be prodigious and in the long run hard to satisfy. This conclusion is strengthened by the fact that Putnam believes our coal resources have been vastly overestimated, so these reserves cannot be counted on too strongly as a possible source of liquid fuels.

Growth of Demand

Elsewhere in his text, Putnam indicates that the demand for energy in the world today is in an "explosive" stage of growth. He particularly refers to the demand which is building up in the under-developed countries of Asia, Africa, and the Middle East, where current demand is low. To illustrate the tremendous potentialities in these areas, the reader might note here that if the world population of 2½ billion people today used oil at the rate of 17.3 bbl per capita per annum, which is the amount used in the U. S., the total world demand would be at the present time some 43 billion bbl per annum, or nearly 120 million bbl daily. This again is mere arithmetic, but the demand abroad is growing rapidly, and what Putnam envisages as the demand for the year 2050 is based on a population figure approximately double what it is today, with every person using on the average half as much oil as a person in the U. S. is using today.

When viewed in this light, the demand figures cited do not seem as unreasonable as they might at first appear. This will be particularly true if peaceful conditions prevail for the next 100 years and the economic lot of the average citizen continues to improve. If this is true, world population may very well total more than 5 billion people at the end of the 100-year period.

Pattern of Future

All of these figures are only indicative of a possible pattern of the future. They raise, of course, an interesting question over which there can be much debate and but little conclusion. That is to say, how long and how far can our rapidly developing mechanical civilization continue with its dependence on fossil fuels (coal and oil) even allowing for the growth of the uses of atomic energy. After looking at the predictions of the past, the writers are sure of only one thing — and that is the predictions over any long period are likely to be wrong.

One suspects that if we turned up the right papyrus of the time of the great Seti the First, Pharaoh of the Egyptians 2nd Empire in the year 1300 B.C., one would find bitter complaints by the superintendent of his Sinai copper mines that they were running out of smeltable ore and that with the shortage of copper Egypt's civilization would then lack armament and become the prey of immense evils. Since the dawn of histoy civilization has always seemed in peril. Today, with the figures cited, a good case can be made for the decline of the age of the machine. Such a conclusion, however, would not have allowed for that most important asset of our civilization — the ingenuity of the human mind. There may well be many undiscovered sources of energy. The Curies when investi-

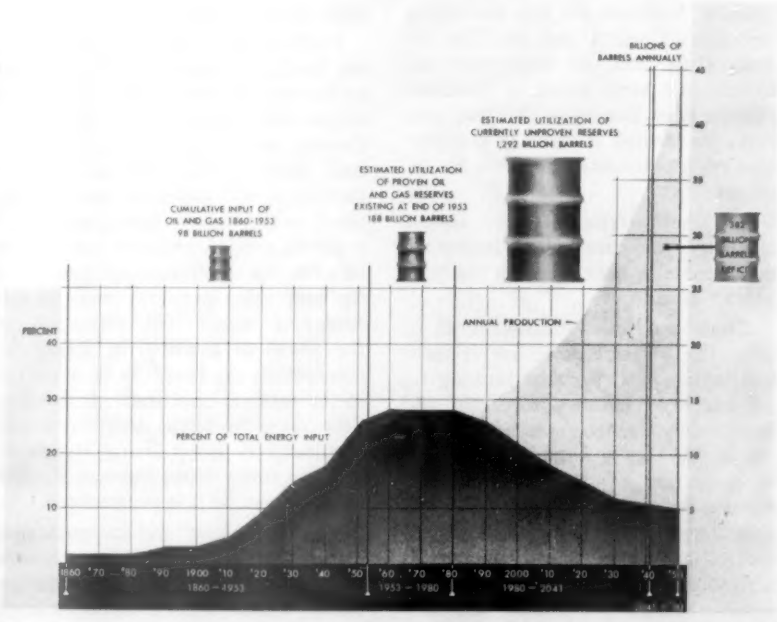
BILLIONS OF BARRELS ANNUALLY
ESTIMATED UTILIZATION OF CURRENTLY UNPROVEN RESERVES 1,292 BILLION BARRELS
ESTIMATED UTILIZATION OF PROVEN OIL AND GAS RESERVES EXISTING AT END OF 1953 188 BILLION BARRELS
CUMULATIVE INPUT OF OIL AND GAS 1860-1953 98 BILLION BARRELS
ANNUAL PRODUCTION
PERCENT
PERCENT OF TOTAL ENERGY INPUT
1860 '70 '80 '90 1900 '10 '20 '30 '40 '50 '60 '70 '80 '90 2000 '10 '20 '30 '40 '50
1860 – 1953
1953 – 1980
1980 – 2041

Fig. 3 — Energy input of hydrocarbon fuels and use of cumulative world reserves. 1860-2050 estimated.

TABLE 2 — SAUDI ARABIAN OIL FIELDS
Arabian American Oil Co., New York, N. Y.

Line Number	Field	Producing Formation: Name, Age and Depth	Year of Discovery	Oil Production: Area Proved, Acres	Oil Production: Barrels Total Produced to June 30, 1954	Total Wells Completed to June 30, 1954	Producing Wells	Non-producing Wells	Character of Oil: Gravity A.P.I.	Character of Oil: Sulphur Per Cent	Producing Formation: Character (c)	Producing Formation: Est. Porosity Per Cent	Estimated Prod. Thick. Avg. Ft. Net	Structure (d)	Deepest Zone Tested to June 30, 1954: Name	Deepest Zone Tested to June 30, 1954: Depth of Hole in Feet
1	Abqaiq	Arab Zone U. Jur.												A	Fadhili Zone	11,209
1A		'C' Member	1940	15,900	892,036	1	1	0	22.0	3.10	OL-DL	20.5				
1B		'D' Member	1941	86,400	979,016,475	65	42	23a	37.6	1.36	OL-DL	20.9				
		Hadriya	1947	27,400	122,134	1	1	0	35.5	—	OL-DL	—				
2	Abu Hadriya	Hadriya Zone M. Jur.	1940	—	9,579	2	0	2	36.0	1.69	OL-DL	—		A	Hadriya	10,220
3	Dammam	Bahrain Zone M. Cre.	1936		965,412						S				Fadhili	8,627
3A		Arab Zone U. Jur.	1938		307,164,702	41	28b	13	35.3	1.45				DF		
3B		'A' Member		11,600							OL-DL	18.6				
3C		'B' Member		9,300							OL-DL	21.7				
3D		'C' Member		7,100							OL-DL	25.4				
3E		'D' Member		2,900							OL-DL	20.7				
4	Fadhili	Fadhili M. Jur.	1949	1,900	—	1	0	1	38.0	1.11	OL-DL	11.3		A	Fadhili	10,675
5	Ghawar	Arab Zone U. Jur.	1948											A	Arab Zone	7,813
		'D' Member		497,200	438,385,807	110	59	51	34.5	1.8	OL-DL	21.2				
6	Qatif	Arab Zone U. Jur.	1945			12	9	3						A	Arab Zone	7,615
6A		'C' Member		21,300	23,271,451				28.0	2.5	OL-DL	16.8				
6B		'D' Member		16,200	31,669,087				38.6	1.4	OL-DL	14.5				
7	Safaniya	Bahrain Zone M. Cre.	1951			16	0	16	27.0	3.06	S			A	Zubair Equivalent	7,649
7A		Upper Member		69,300	—							27.0				
7B		Lower Member		56,300	—							28.0				

(a) Includes two gas injection wells and one well being repaired
(b) Includes three producing gas wells
(c) DL—dolomitic limestone; OL—oolitic limestone; S—sandstone
(d) A—anticlinal; DF—dome with faulting

gating the effect of a mineral pitchblende, from Joachimstal in Austria, on a photographic plate some 60 years ago certainly did not foresee the Oak Ridge plant of the Atomic Energy Commission.

Proved Oil Reserves

The most massive of the world's proved oil reserves lie today in the Middle East. In fact, the reserves there are rapidly approaching the fabulous amount of 100 billion bbl. The prognosis is for future growth. We also have growing reserves in Colombia and Venezuela, while the active operations in Peru are the portent of increased reserves in that country. Reserves are also increasing rapidly in Canada and the East Indies. Then, too, an important discovery has been made in southern France near Bordeaux. Mexico also looks as though it were in the process of a substantial increase in reserves.

The news from Russia, always shadowy, indicates that important new fields are developing in the Stalingrad area.

There are some lessons in all of this. The French discovery is most instructive. The French thinking on oil has been military in origin and has usually been connected with defense. "As this is a munition of war, we must find it ourselves," said they. Hence, followed the long and abortive campaign by the government to find oil in France. It was in the main a failure, but a change was made recently. Private prospectors are now encouraged and the net result is that Standard of New Jersey has found what promises to be a major field. An American writer once made the generalization that oil was kept from discovery largely because of men's laws. It is all too true.

The World Community

This raises another political point. Except for the U. S. and Canada, the countries with large reserves are not large oil consumers. Some countries have coal, others steel, others copper—none are self-sufficient. Unfortunately, the accidents of geology and geography did not distribute the world's raw materials equitably among the nations. The result is that the nations are mutually dependent upon one another.

Further than that, politically, we are busily engaged in following out to its end Wilson's political dictum on the self-determination of peoples. From it are springing numerous new and often untried political entities created in the name of freedom. In other words, we are fractionating our political world, while in contrast to this increasing division of peoples is the increasing need for unity in our economic world. The prosperity of the world as a whole is largely dependent on the free flow of materials in the international trade. If this free flow halts, the world drops back economically to lower living standards, and we suffer from increased political tensions. So it is everywhere.

So nationalism and independence at their very root must recognize the need for the closest cooperation among nations on the economic level. In this respect all nations have responsibilities to the world community. We must accept this as a matter of law and custom (often stronger than law), or else we cannot continue our economic progress. Sovereignty is a meaningless thing if it does not lead to better relations with others in the community of nations. If political events and ideas block this interchange of goods and services the world is the worse for it.

Arabian Development

Let us turn for a moment to the Persian Gulf and more particularly Arabia. There is presented a table showing the present state of development.

The fields in Arabia are of great size. Ghawar will probably exceed 800,000 acres in area. It is probably the world's largest discovered oil field easily surpassing in total reserves the Burgan field. Yet the geologists believe that the exploration of Saudi Arabia has really just begun. Natutrally we see no world oil shortage now. Similar conditions for favorable exploration exist elsewhere in the Middle East and proved reserves for the area now approach 100 billions of barrels. The problem there, despite the future enormous demand figures cited are for the next decade the problems of politics, economics, and strategy. If we were all statesmen, it would be one thing, but the classic remark of the Irish Parliamentarian "what the hell did posterity ever do for me" still applies.

The lease owner in Texas wants to extract the oil he has struggled so hard to find and convert it into something tangible for himself be-

fore he is gathered to his fathers. The politician in "X" country wishes to see revenues flow to his government to pay for schools, roads, and the other things his people need during his term of office so that he will receive the political rewards arising from a successful administration and prosperous electorate. These are human desires, and one can well sympathize with them. Then, too, other industries, overwhelmed by the dynamics of our own extraordinary industry, attempt to limit through political means the markets for oil. One country taxes fuel oil heavily so that it will not compete too strongly with its national coal industry whose miners, largely communists, are a special political problem. The great Coal-Steel authority in Europe is deeply concerned over competition between fuels. Yet if all the world today consumed oil at the rate we do here in the U. S., it would be utterly impossible to supply the market demand.

Solution to the Problem

The problem — and it is everybody's problem — is to equate our long-term needs with our short-term problems, and at the same time not to lose the dynamic spirit that moves the industry. After all, the great results in the Middle East are due to the scientific application of techniques developed in the United States. It is the continuing experimentation carried on by myriads of different individuals that creates these matchless techniques. It is characteristic of such a system that some individuals lose, but the glittering prize of success is there for all to see and to enjoy if they are brave enough and fortunate enough to seize it. So it should continue. It is the contrast between the free world and communism. In the free world we can experiment; some of us may come to disaster but the end is progress and change, not a crystallized and rigid economy. Very often we fail to realize that in our economic world the price of progress is ceaseless experimentation. All of us at times have an unfortunate penchant for the tidy and complete solution of problems. In this we are one with the believers in the Chimeras of the universal solvent and the philosopher's touchstone. This is a mental temptation to all of us, for there are those among us who in the name of order would organize our economic world into that stagnation which comes from a system without change.

The problems of over-supply can only be solved by cut-and-try methods, and in the long run we must remember these over-supply problems usually turn into equally temporary shortages. It is these very changes that sharpen men's wits. Nevertheless, out of the situation in the Middle East may come new patterns of supply in which governments and companies will work together. The Iranian Agreement is an example.

The immense supplies of liquid fuels that can be made from natural resources other than oil from wells hedge us about with a competitive wall which will not permit prices to get out of hand. If prices rise too rapidly, capital will flow into tar sand, coal, and shale oil development which is possibly some 20 years away. But in any event, the prospect for the demand for oil products in the future is so great, that in the long run we shall be hard pushed to supply it—this, in spite of the fact that nuclear energy is believed to be about to play a major role by the year 1970.

In the meantime the authors believe that we shall make progress in the field of economics and politics—progress that will preserve these freedoms in which this most dynamic of industries rejoices, and at the same time will guard against its destruction from internal stresses.

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SOME SIDELIGHTS in PETROLEUM'S ECONOMIC PROGRESS

C. O. WILLSON
MEMBER AIME

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This discussion concerns what might be considered the by-product developments and trends, or parts of the whole, within the oil industry which come to the attention of an editor in connection with his daily and weekly tasks.

Future Demands

Predicting yearly petroleum demands has become a somewhat hazardous undertaking in this country since World War II. In some years the projections have varied so widely from actual demands as they have materialized that they have lost much of their value as a guide to operators. For example, most of the projections of a year ago called for an increase in 1954 U. S. demands of 4 to 4½ per cent over 1953. The increase was less than 1 per cent. This means that the actual demand was around 250,000 B/D less than the anticipated level of operation, and that fact accounts for some of the unwanted oil developments of the past year.

It is true, however, that the good years tend to offset the poor ones so that the five and 10-year periods work out, as regards demands, more in line with predictions. With this situation in mind some economists are predicting more than average gains for 1955.

Keeping in mind that in these days of surpluses it is easier and less painful to expand operations than it is to contract them, a gain of 5½ per cent domestic appears reasonable at this time. With a further decrease in exports in prospect we end up with a 4.8 per cent gain in over-all demands.

This will total an estimated 8,483,560 B/D in this country for this year or a gain of 388,560 B/D over the year that has just closed. Of this total gain of 141,824,400 bbl for the entire year it is estimated that 78 per cent will come from domestic crude oil producers, 12½ per cent from imports, and 8½ per cent from natural gas liquids.

Optimistic Outlook

The long-range outlook for petroleum in this country is equally optimistic. It is agreed that exports will continue to decrease until they are largely confined to specialties and part of the U. S. military requirements. But domestic gains will be normal with a growth of 40 per cent predicted over the next 10 years and a minimum of 70 per cent for the next 20 years. A U. S. population of 220 million is predicted over the next 20 years.

This means that the industry can look forward to domestic demands totaling around 13 million bbl by 1974. Assuming a decrease in exports to 150,000 B/D it is apparent that in 1974 total demands (domestic plus exports) will total about 4.8 billion bbl.

Past developments show that the relationship between proved reserves and current production should be in the order of 13 to 1. This means that in 1974 this country should have a minimum of 62½ billion bbl of proved reserves within its boundaries.

Our present reserves total about 36 billion bbl of crude oil and natural gas liquids, which means that 26½ billion bbl will have to be added to our proved reserves over the next two decades.

Domestic Industry Must Grow

Total demands over the 20-year period will total approximately 78 billion bbl. How much of this will be supplied by imports cannot be accurately projected at this time, because the amounts will depend on public and industrial policies not determinable at this time.

But assuming that imports will be called upon to supply about 13½ per cent of the total demand, the domestic petroleum industry will be responsible for 67½ billion bbl applied to current needs during the next 20 years. Adding the 26½ billion bbl of additional proved reserves to this domestic total, we arrive at a figure of 94 billion bbl of crude oil and natural gas liquids which must be found in this country over the next 20 years.

What this means can possibly best be visualized by comparing the future with the past. This country has produced approximately 50 billion bbl of crude oil since the Drake discovery of 1859. We have discovered an additional 31 billion bbl (exclusive of natural gas liquids) in proved reserves or a total of 81 billion bbl of crude oil.

Thus the domestic oil industry over the next 20 years must discover considerably more oil than it found over the last 95 years. This means entirely new producing areas, the extension of proved fields, further substantial improvement in recovery methods, and returns for crude oil and products which will justify the record expenditures which will be necessary.

*Willson was editor of the Oil and Gas Journal for 17 years and is now consulting editor.

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Evaluating the Future

One way of visualizing the task ahead is to evaluate the future on a basis of what has happened over the past five years, during which new records have been established annually in total U. S. drilling, wildcat drilling, and in yearly supplies.

It has been necessary to drill a total of 236,825 wells over the past five years, of which 51,750 have been wildcat tests. This drilling added to existing wells has provided a crude oil production of 13.2 billion bbl and in addition has added 7.6 billion bbl of liquid petroleum to proved reserves. Thus this record drilling has made less than 21 billion bbl of crude oil and natural gas liquids available over a five-year period.

Current data on inventories and market trends indicate that we have excess petroleum supplies in this country at this time and this situation should be corrected. But the foregoing data are proof that for the entire 20-year period the search for new oil in this country will have to be expanded to a scale never before equaled in this country.

Equally important is the fact that producing, manufacturing, transportation, and distribution must also establish new yearly records in the building of new facilities with steady improvement in operating practices. *These requirements obviously justify the expenditures now being made in petroleum research and development which now exceed those of any other industry financed by private expenditures.*

Natural Gas

No analysis of petroleum demands in this country would be complete which did not include natural gas. The domestic consumption of natural gas has increased percentagewise much more rapidly than has oil in recent years, the gains since 1939 totaling 255 per cent.

Present marketed consumption in this country is now running in excess of 9 trillion cu ft yearly. The magnitude of this demand can possibly best be understood when it is realized that in oil equivalent it is now in excess of 4,000,000 B/D or about 50 per cent of the total liquid output of oil.

Spokesmen for the natural gas industry have said the production and transmission of their product will continue to be expanded around 8 per cent yearly over the next few years at least, provided the industry is permitted to conduct activities with no more interference from the federal Government than was in effect previous to the U. S. Supreme Court decision of last June affecting production and sale of natural gas. No long-range predictions as to the expansion can be made until this issue is decided.

This fact should be kept in mind. *Oil and natural gas have become increasingly competitive.* Natural gas has taken important markets in industrial, commercial, and home-heating fields which, if the gas had not been available, would have gone to oil. Fortunately in our rapidly expanding postwar economy so far there has been room for both without undue marketing difficulties for either.

It is agreed that this generally satisfactory situation could change. There are increasing complaints that natural gas is getting the lion's share of the new home-heating markets in certain areas. Important fuel markets in the industrial and commercial fields have been lost to natural gas over the past year.

Because of these developments, all branches of the oil industry have a stake in the needed adjustments which will advance natural gas prices at the wells and in wholesale and retail markets so that they will become comparable on a Btu basis to oil. Otherwise natural gas may become a bearish factor in petroleum markets generally.

100 Octane Motor Fuel?

One of the more significant developments of the past year has been the steady increase in octane ratings of motor fuels—particularly the premium grades. The predictions of some that the octane race of recent years would level off in 1954 have not been borne out.

Now come the 1955 motor vehicles with a record average increase of 0.4 in compression ratios in engines and an increase of more than 30 in brake-horsepower. Compression ratios in the new cars range up to 9.1. Of special importance are the compression ratio increases in the popular-priced cars. Formerly the manufacturers of those cars which represent the great bulk of the automotive market were accustomed to recommend the use of regular-grade gasolines as fuel, but they are now definitely in the premium motor-fuel class.

All developments point to a continuance of this trend toward higher compression ratios and correspondingly higher octane ratings. The new-car buyer demands greater performance along with changes in body design. There is no consumer demand for economy in engine performance, including fuels.

Some manufacturers make no secret of the fact that they are looking forward to compression ratios up to 12 to 1. The higher compression ratios are now being supplied with premium gasolines ranging from 91 to 98 octanes. Chemical additives which aid in the smooth performance and which aid engines in other ways have become common.

The higher-compression engines of last year required the top of the premium octane spread. Past history indicates that before the year closes those oil companies which have led in the octane race will advance from the 94 and 95-octane levels. Ninety-eight octane fuel has been introduced since the first of the year in important areas.

Assuming there is no change in car-owner demands, the refining and marketing branches of the oil business appear headed toward 100-octane motor fuel, not five to 10 years from now but starting soon—possibly this year.

What this means in equipment and methods only the refiner can visualize. It will mean that the catalytic cracking and reforming operations which have grown so rapidly since World War II must be further expanded and processing methods now confined to specialty products will be adapted to large-scale operations. New techniques now in the development and pilot-plant stage may become a part of the routine operations of the future. Here again current research and development programs are of major importance.

Product Pipe Lines

In this postwar period growth in crude oil transportation has kept pace with the available supplies and the expansion of natural gas transmission facilities has far exceeded any previous period. Tanker capacity has been increased to the point where, on a world-wide basis, surpluses prevail.

While not so large in expenditures and volume of

product as these long-established media, the postwar trends in product pipeline transportation have special significance in reflecting changed conditions within the oil industry.

Starting in 1930 the original pipelines were built by users with the tariffs about equal to the rail rates between the same points. Pipeline revenues on this basis were substantial and rapid payouts resulted to the refinery owners.

More recently there have been special regulations for the product lines promulgated by the Interstate Commerce Commission, including ceilings on distributed earnings. One of the results has been reductions in tariffs so that present rates to representative points are usually one-third to two-thirds the rail rates. Operations are now comparable to those of crude oil systems in many respects including situations in which the owning and operating companies have no connections with either refining or marketing and act solely as transporters.

Costs are not only lower than rail rates but the product lines now parallel many inland waterways long considered the cheapest method of transportation in product shipments to interior points. Furthermore, while started on the operating principle of moving large quantities for long distances, improvements in operating practices and higher competitive rail rates have made short product lines of small capacity increasingly attractive.

Probably the most significant change brought about by the product-pipeline growth has to do with marketing. Whereas for many years a large part of the savings in costs over rail movements usually accrued to the refiner-seller, the recent competitive trend has been to pass on the savings to the jobber-buyers and ultimately to the dealers and consumers.

While the long-established practice of quoting refinery prices by refinery areas on products continues in daily and weekly publications, actual sales at pipeline terminals largely determine the going market in large sections of this country. The netback to the seller in these cases is under the published quotations. This has established a competitive situation in which the outlets for refiners without product pipeline connections are usually confined to local needs with truck and short rail hauls.

This type of competition obviously points to the further rapid growth in product pipelines. Some observers conceive of vast trunkline and lateral systems—several interstate in scope—connecting to practically all population centers exclusive of coastal points. Such a program in its main details has the support of those directing the nation's defenses who favor underground transportation operations of all kinds.

Natural Gas Liquids

This trend in product pipeline is certain to include further growth in shipments of natural gasoline and liquefied petroleum gases, now under way on a limited basis. Producers of casinghead gas and the manufacturers of natural gasolines have long been dissatisfied with the prices received for the finished products. The natural gasoline products are usually sold under the posted prices for crude oil with which the casinghead gas is produced.

This price disparity is even more apparent when the going markets for liquefied petroleum gases are considered. Prevailing prices for butane and propane, the principal products, generally range during the year from 2 to 4 cents per gallon in the Southwest with propane often disposed of in gas lines during the low-consuming summer period with little or no return to the producer or manufacturer.

Investigations have shown that this pricing situation for natural gasoline and LPG could be improved if there were lower transportation costs between plants in the field and refineries or distributing points in the consumer areas often a thousand or more miles from the sources of supply. It appears certain that the transportation of both natural gasoline and LPG in multiproduct lines will expand to the end that delivered costs can be lowered and higher prices prevail for the producers of casinghead gas and the manufacturers of natural gasolines and LPG.

With the current production of natural gas liquids in excess of 700,000 B/D there have been building programs under consideration which would provide entirely new pipline systems for their movement from the plants in the fields to refineries, bulk terminals, and other distributing facilities.

More Highways

Optimistic predictions of future petroleum demands with gasoline continuing to be the principal "money product" have been presented. Such programs always assume there will be no developments outside the direct control of the oil industry which would tend to restrict the expected growth.

Investigations made within the petroleum and automotive industries and the federal government are in agreement that the expansion of improved highway systems and streets in towns and cities have failed to fill the needs of all classes of motor-vehicle operators. Inadequate parking facilities are a phase of this problem as are increasing deaths and injuries from highway accidents.

The common expression is that motor vehicles in use have increased twice as fast as have suitable highways and now a crisis is here because of this disparity.

Surveys have shown that gasoline consumption per vehicle has suffered in some parts of the country as a result of highways and street conditions and these situations will become intensified if the problem is not solved.

Entirely new interstate superhighway systems are needed as well as improvements for those already in use. Charles F. Kettering, then head of General Motors' research and development, pointed out years ago that this country's highway system was adapted from country roads laid out originally to accommodate the occasional horse and buggy and not heavy traffic moving 40 to 70 miles per hour.

Toll highways are a partial but not a complete answer to this problem. Car and truck owners who are paying out 5½ billion dollars yearly in the form of state and federal gasoline taxes, federal lubricating-oil taxes, registration fees, and excise taxes are entitled to freeways for most of their highway and street requirements. It is said, however, this tax income is inadequate to carry out the program under consideration.

Programs providing for large new expenditures over the next 10 years are being outlined. Partially they are being justified for national defense. There is agreement as to the main features.

It is not so clear how these mammoth programs can be paid for. Finding the solution is a challenge to both the automotive and petroleum industries as well as to those charged with the responsibility of advancing the nation's entire economy and defenses. The future growth of the petroleum industry is directly involved.

Foreign Operations

While there was a small decrease in crude-oil production in this country (exclusive of natural gas liquids) in the year that has just closed, gains in foreign countries exclusive of the Russian-dominated areas totaled 10 per cent. A preliminary estimate shows that U. S. crude oil production averaged 6,330,000 B/D in 1954 while that of the foreign noncommunist countries averaged 5,856,000 B/D.

It is necessary to keep in mind that 1954 production data were not an accurate criteria of what happened in available production supplies, and they have not been in recent years. The year 1954 was a period of excess available supplies in most of the major oil-producing countries and curtailments were necessary to keep output in line with current needs.

For several years the changes in proved reserves which have greatest worldwide significance have been in foreign countries and 1954 was no exception. Proved crude oil reserves of noncommunist countries outside the United States on Dec. 31, 1954, according to year-end estimates totaled 118,200,000,000 bbl, a gain of 18,664,000,000 bbl for the year. The proved reserves of the Russian-controlled countries add another 10 billion bbl representing a small yearly gain according to the best available estimates.

Thus we have a world situation with 164 billion bbl of proved reserves of crude oil and natural gas liquids as of the first of the year, of which 22 per cent are located in this country, 72 per cent in the remaining free countries, and 6 per cent in Russian-dominated areas.

We are concerned here with only the Middle East and Venezuela whose large-scale operations have been controlling in international oil activities since the close of World War II and which, because of imports to this country, have had an important bearing on domestic operating trends.

Proved reserves of the Middle East the first of the year were estimated at 97,459,000,000 bbl, a gain of 19,244,000,000 bbl or nearly 25 per cent for the year. The increase was 12 to 13 times greater than that of this country and in volume the total proved reserves of the Middle East are now 2½ times larger.

The Middle East countries included are Iran, Iraq, Saudi Arabia, Bahrain Island, Kuwait, Neutral Zone, Qatar, and a small quantity in Turkey.

The mammoth gains in Middle East reserves the past year did not come primarily from new discoveries but largely through extension tests and a few development wells which enabled existing reserves to be reevaluated upward. It is often pointed out that proved reserves in the Middle East representing about 60 per cent of the world total were found with the drilling of fewer than 200 wildcat tests. In contrast more than double that number are drilled each week in this country.

The current data for Venezuela are not as spectacular as those of the Middle East but they do reflect developments which have made it the second largest oil-producing country. Its proved reserves now total about 11 billion bbl, a 10 per cent gain for the year. Its production increased 6 per cent to a 1,874,000 B/D average in 1954. Venezuela by wide margin is the largest single exporting country of the oil world.

Production by Wells

In the United States the average daily production of crude oil per well was about 13 bbl last year—slightly more if the production of natural gas liquids is included. A total of 491,509 wells were producing. This United States figure compares with a daily average production of 244 bbl from the 7,680 wells in Venezuela.

However, the Middle East production was obtained from 540 wells averaging 5,000 bbl daily. The kingdoms of Iraq and Saudi Arabia and the independent shaikdom of Kuwait accounted for 93 per cent of the crude oil production of the Middle East last year.

For these three countries the average production per well was 6,832 bbl with a high of 8,400 bbl for the 74 wells in Iraq. These data reflect the wide variations in crude-production costs among the three major world supply sources—United States, the Middle East, and Venezuela.

Other Expansion

Much additional data including comparisons could be presented having to do with the finding, production, and the underground accumulation of crude oil. A complete report would show that the 210 per cent increase in crude oil production in the noncommunist countries outside the United States since World War II has been paralleled with expansion in refining, transportation, and distributing facilities.

While the greatest growth in refining has been in Western Europe and Great Britain, the record expansion has included plants adjacent to the newer crude oil supplies and such widely scattered points as India, the Philippines, and Australia. The Eastern Hemisphere is now in a position to be self-sufficient in crude oil for the first time in oil history with excess supplies available to the western part of the world.

U. S. Imports

We are concerned here with developments which have a direct bearing on domestic operations. Foreign oil expansion has not been confined to foreign outlets. As a result primarily of the rapid growth in Venezuela and the Middle East, imports of crude oil and products to this country have jumped from 365,480 B/D in 1945 to 1,037,200 B/D for the first nine months of 1954, a gain of 184 per cent.

At the same time oil exports from this country dropped from 501,320 B/D in 1945 to 353,530 B/D the first nine months of last year, a decline of 29 per cent. This country has been a net importer of petroleum on a widening basis since 1946.

This increased competition of the new foreign petroleum supplies reflected in enlarged imports and decreased exports has been accompanied by a defense policy of encouraging the domestic industry to expand its producing, transportation, and refining capacity in excess of current needs. This program along with the import-export situation has resulted in an excess of current available crude-oil production estimated to be 1,750,000 to 2,000,000 B/D over the MER.

There is also greater over-all refining capacity in this country. The excess in the case of some plants is substantial, resulting in operating hardships. Over the past 18 months these developments have brought weakness in the domestic product prices.

This has worked a particular hardship on the independent refiners who are largely or solely dependent on refinery margins for profits. There has been some improvement in refinery markets over the past two months. Should it continue, a market crisis which might have extended to crude oil will be averted.

International Companies

Domestic oil policy has been complicated by the fact that the foreign operations of an important group of American oil companies have been expanded to the point where there are now a group of companies whose perspective is essentially international in scope. These are the Standard Oil Co. (New Jersey); Standard Oil Co. of California; Gulf Oil Corp.; Socony-Vacuum Oil Co., Inc.; and The Texas Co. These companies through subsidiaries control the great bulk of the operations in the Middle East and Venezuela. The remainder is largely in the hands of two other major international companies, British Petroleum Co., Ltd. (formerly Anglo-Iranian Oil Co., Ltd.,) and the Royal Dutch-Shell.

The seven companies are associated in a consortium which this year expects to make an average of 300,000 B/D of crude oil or products available in world markets. This program which will be expanded steadily in later years, and thus adds to the importance of the Middle East in international oil operations.

In 1953 the five American companies produced 4,401,120 bbl daily of crude oil and of this total 63 per cent came from foreign fields and 37 per cent from domestic sources.

An estimate at the close of 1953 credited the five companies with proved reserves totaling 60,431,000,000 B/D of which 86 per cent were in foreign countries and 14 per cent in this country. During 1954, as previously explained, there were large increases in proved reserves in foreign countries in which the five American companies had the major charge. Thus the foreign reserve position of these companies has become more dominant in the companies' operations over the past 12 months.

There, of course, can be no criticism of the rapid expansion of the foreign operations of these five international companies. It is indeed fortunate, not only for this country but for free peoples everywhere, that foreign oil operations outside the communistic-controlled countries are largely in the hands of these five American companies and British Petroleum Co., Ltd., and the Royal Dutch-Shell, which are owned and operated by the nationals of friendly countries.

But these desirable developments do not alter the fact that the size and scope of these operations in other countries have gradually brought changes in fundamental conditions in the international oil industry and a frank appraisal needs to be made as a basis for a sound petroleum policy covering the entire world.

Conclusions

Without attempting to analyze all the vital issues involved, here are a few situations which appear to have major significance:

1. The base of the world oil industry has moved from the Western to the Eastern Hemisphere, centering in the Middle East. This conclusion is derived from the East's wide dominance in reserves with comparatively low production costs including cost of finding in the Middle East. There is no evidence that this comparative situation will change soon.

2. Second to the Middle East in world markets is Venezuela. The two areas last year accounted for 78 per cent of the world's crude oil production exclusive of the United States and the communistic-dominated countries. Their percentage position is even stronger when measured in terms of oil moving in international trade.

3. Either the Middle East or Venezuela or both are now in a position to deliver crude oil or the principal products at lower costs than any other source of supply over most of the world. This cost advantage includes all the costal areas of this country.

4. The United States which previous to World War II was the most important factor in world markets now occupies a minor position. Its exports are largely confined to special products, some military needs, and shipments to nearby areas. These exports have been decreasing in volume since the close of World War II, and the outlook is for a continuance of this trend until they become a very small part of the total oil demands within the boundaries of this country.

5. Five American oil companies (Standard of New Jersey, Standard of California, Texas, Gulf, and Socony-Vacuum) have now become major international operators with greater oil production (one exception) and far greater reserves in foreign countries than they have in this country. These developments in the comparative domestic-foreign position inevitably must be considered in the operating policies of the companies concerned. Several additional United States companies have positions of minor importance in operations outside this country.

6. Imports of crude oil and products to this country originating in the Middle East and Venezuela and smaller quantities from other countries are desirable. This assumption has to do with matters of international trade, the conservation of domestic supplies, and the need to aid American companies in maintaining strong positions in oil operations outside this country.

7. But it is agreed that these lower-cost imports should not be enlarged to the point where they become controlling in domestic operations. This involves the entire economy of this country, and the ability of the domestic oil industry to furnish oil supplies — with outside supplies cut off — for a possible national emergency as it did in World Wars I and II.

8. Returns for crude oil and products in this country should support the mammoth programs ahead of finding new oil and producing it, along with adequate returns in all other divisions of operations. The expansion of research and development programs, which have had such a vital part in the postwar growth of the oil business, is an essential part of plans for the future.

9. How this country, as a matter of business and public policy, can best protect the domestic and international oil operations of its nationals presents problems of many ramifications at this time. The well-being of all concerned demands that immediate and long-range solutions be found. ★★★

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Low in height and compact, this new Guiberson stripper speeds up running or pulling tubing because it seals automatically. Rubber requires no tightening or adjustment. Cup-shaped rubber is specially designed to be tear resistant — specially compounded to resist damage from oil, gas or well fluid. Reinforced with steel wires and bushing.

Bayonet-type latch on cover plate makes it easy and quick to remove or install rubber. Handles lock the cover on the body. Cover plate accommodates Guiberson Tubing Spider. Body may be tapped for two 2″ side outlets on special order. Pressure rating, 750 p.s.i. working pressure, 1500 p.s.i. test pressure. For 2″, 2½″ and 3″ tubing, and for flange sizes 6″-400, 6″-600, 6″-900, 8″-400 and 8″-600.

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FORMATION AND CASING TESTING — JOHNSTON

You can now use emulsion muds in exploratory wells with no danger of affecting analysis of cores and cuttings

Those who visited our booth at the AAPG meeting (Los Angeles Biltmore, November 11 & 12), saw a demonstration under black light that proved some interesting facts about emulsion muds. An emulsion mud will speed up the rate of penetration by slicking up the hole, drastically lowering drill pipe torque, reducing wear and tear on equipment, depositing a thin mud cake, reducing filtrate loss, helping keep a hole "to gauge", and generally eliminating many sources of drilling troubles.

But geologists have repeatedly objected to the use of emulsion muds in exploratory wells (and rightfully so) because the oil in the mud contaminates cores and cuttings and makes it impossible to tell whether oil in the samples comes from the formation or from the emulsion mud. The only solution to the problem is to use a non-fluorescing oil for the emulsion mud. No-Glo is the only non-fluorescing oil commercially available today and our widely scattered field jobs to date have proved conclusively that No-Glo does not become colored or fluorescent under drilling conditions.

At the other extreme, core analysts have told us that there is no need to go to a non-fluorescing oil—that a diesel oil is adequate—because they can tell the difference in fluorescence and cut between a diesel oil and crude oil. In our demonstration under the black light such was not the case. Diesel looks very much like condensate, and after aging under temperature the unstable hydrocarbons in diesel oil polymerize and oxidize until the the diesel cannot reasonably be distinguished from crude oil.

Well logging crews themselves have conceded that under drilling conditions, diesel oil, stove oil, numerous other refined oils, fluorescing emulsifiers and crude oil all begin to look alike under the ultraviolet light and accurate interpretations are impossible.

No-Glo has improved drilling operations without interfering with geological interpretations, in many diversified domestic fields and in two foreign countries, and has been used with excellent results in an offshore job. For example, No-Glo was used successfully by Shell at Weeks Island, Louisiana (Gonsoulin-Minvielle State Unit #2) from 16,100′ to 18,200′. This was the deepest producing well in the world when completed. Shell also used No-Glo in another well in this field for spotting opposite pipe that was tightly stuck at about 9,600′ in a "keyseat". No-Glo not only freed the stuck pipe but prevented complications by introducing no fluorescence to the mud system. Others are now using it in wildcats in place of crude oil for freeing stuck pipe. A supply of 40 to 50 barrels at the rig ready for use, may save an expensive fishing job in case pipe becomes stuck. It is low-cost insurance.

No-Glo oil is a specially treated oil which may be added to any clay-water mud in the normal manner. A U. S. Patent has been allowed to Oil Base, Inc. on the use of No-Glo, and numerous foreign patents are pending. Licenses to oil companies and their subsidiaries to use No-Glo oil on a nominal royalty basis will be considered upon request.

If an emulsifier is to be used, White Magic is a whitish, readily-soluble, powdered emulsifier that does not fluoresce.

Together with No-Glo oil White Magic forms an excellent low-water-loss emulsion mud that has a flexible weight range, is electrically conductive, easily controlled and may be used without caustic soda for moderate pH ranges of drilling mud.

There are also many instances where pipe dopes gradually contaminate the mud and interfere with core and cutting interpretations. To prevent this hazard, insist on No-Glo Thread Lubricant when drilling wildcats even though an emulsion mud may not be required. No-Glo Thread Lubricant will not fluoresce and contains no fluorescence suppressors. Packed in 50 lb. pails.

Again, due to OBI research, a well-recognized need but hitherto unanswered problem has been solved. If you run into trouble during drilling and would like to switch to an emulsion mud that will not affect core analyses, No-Glo is the *only* answer.

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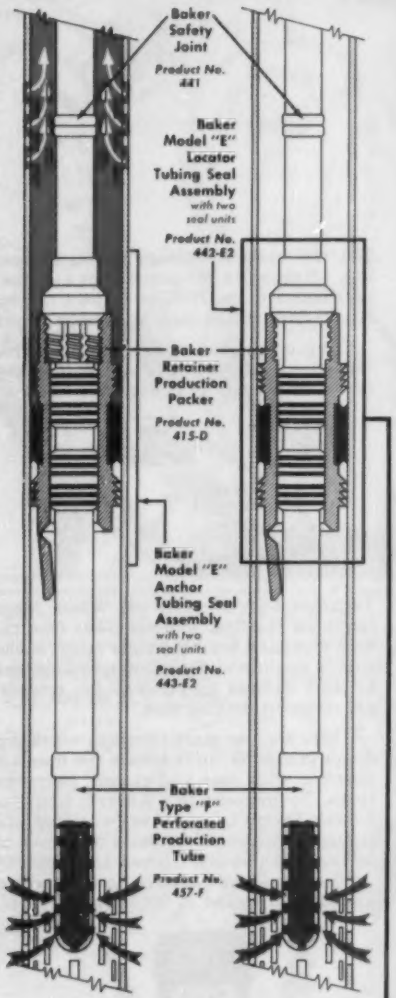
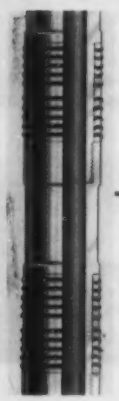

Baker Safety Joint
Product No. 441
Baker Model "E" Locator Tubing Seal Assembly with two seal units
Product No. 442-E2
Baker Retainer Production Packer
Product No. 415-D
Baker Model "E" Anchor Tubing Seal Assembly with two seal units
Product No. 443-E2
Baker Type "F" Perforated Production Tube
Product No. 457-F
TYPICAL DUAL ZONE HOOKUP
TYPICAL SINGLE ZONE HOOKUP



Right: Picture shows actual detail of seal units

Do you know that with only ONE Baker Retainer Production Packer you can equip your well for *either* SINGLE ZONE or DUAL ZONE production? And that you can accomplish *any* type of completion for *any* method of production to meet *fixed* or *changing* well conditions?

A single Baker Retainer Production Packer will also outperform many specialized tools when used as a TESTING PACKER – SQUEEZE PACKER – GAS LIFT PACKER – PERMANENT COMPLETION PACKER – WATER FLOOD PACKER – GAS INJECTION PACKER – CORROSION CONTROL PACKER – TUBING ANCHOR – ONE-WAY BRIDGE PLUG – PERMANENT BRIDGE PLUG.

Every production man should be familiar with the many operating advantages of this "Universal Type" Packer, which include . . .

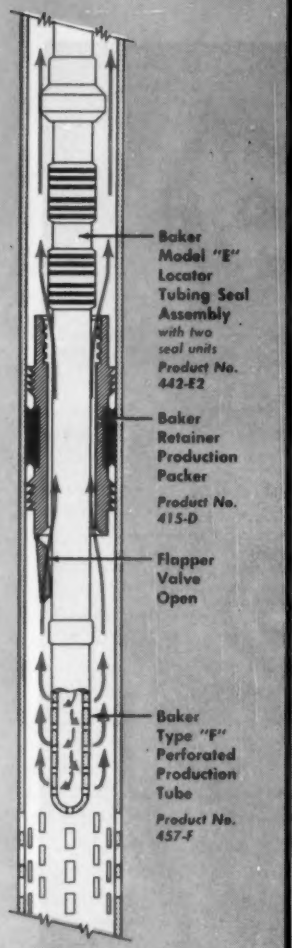
WIRE LINE SETTING—The packer can be set with *wire line speed and accuracy*, using the same set-up just used for perforating. The Baker Packer also can be set on drill pipe or tubing.

SETTING UNDER HIGH PRESSURE—By using a lubricator, the Baker Retainer Production Packer can be set under high pressure. From the moment it is set, the self-contained, flapper-type, back-pressure valve closes and isolates pressure below the packer.

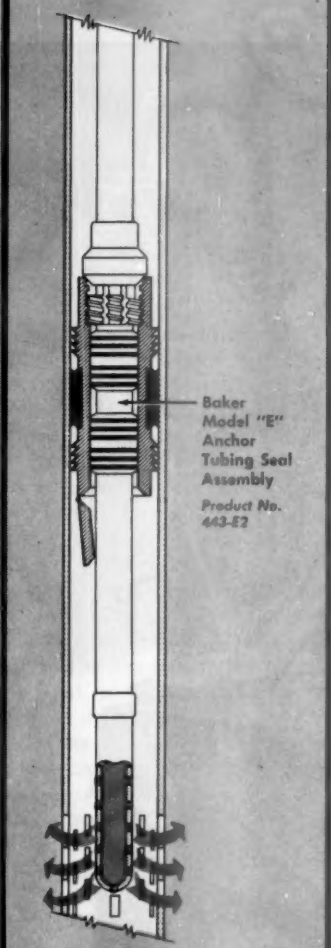
TUBING STRING IS ALWAYS "FREE"—That valuable string of tubing—whether 1,000 feet or 16,000 feet in length—can be removed by simply picking up the tubing weight.

EXCESSIVE "SET-DOWN" WEIGHT OR TENSION NOT REQUIRED—Even when squeezing, formation fracturing, or producing at any depth under pressure, a perfect pack-off is maintained independent of excessive set-down weight, or tension.

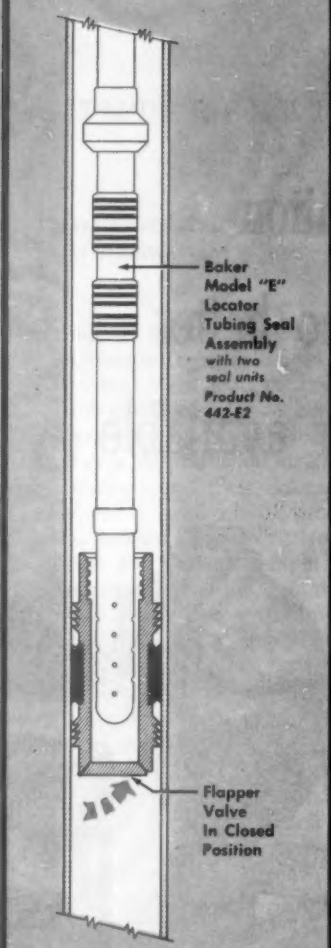
HOLDS PRESSURE DIFFERENTIALS FROM ABOVE OR BELOW—Two sets of opposed slips, and a resilient packing confined by lead and metallic sealing rings, effect a permanent pack-off that will hold any pressure differential *either from above or below the packer* that is safe for the well equipment.


Baker Model "E" Locator Tubing Seal Assembly with two seal units Product No. 442-E2
Baker Retainer Production Packer Product No. 415-D
Flapper Valve Open
Baker Type "F" Perforated Production Tube Product No. 457-F

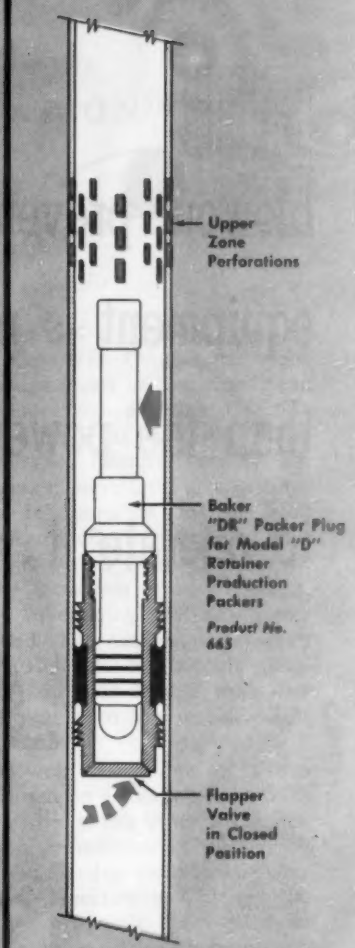
Washing or Circulating—Seals of Locator Tubing Seal Assembly removed from packer bore. Flapper Valve held open by tubing extending below the Packer.



Pressuring Below Packer—Acid or cement squeeze, formation fracture, gas or water injection. Anchor Tubing Seal Assembly is used when high squeeze pressures are required.



Isolate Zone Below Packer—Tubing String removed, Flapper Valve closed. Isolates pressure differentials (squeeze, production) from below the packer.


Upper Zone Perforations
Baker "DR" Packer Plug for Model "D" Retainer Production Packers Product No. 665
Flapper Valve in Closed Position

Temporary Bridge Plug—For working over zones above the packer. DR Plug is run in on Baker Retrievable Cementer and retrieved with overshot.

PACKS-OFF AND HOLDS UNDER HIGH BHT—Baker Retainer Production Packers will hold high pressures under conditions of high temperatures. Hundreds of Baker Packers are in successful service in Southwest and Gulf Coast areas where temperatures in excess of 300 degrees are not uncommon.

RESISTS CORROSION—The cast-iron used in the construction of Baker Packers is far more resistant to corrosion than the casing in which the packer is set, thus making it ideal for permanent installations, or for use in areas plagued with a severe corrosion problem.

EASILY DRILLABLE—The Baker Packer is constructed of drillable cast-iron, and its design supplements the breaking-up action of the bit. Whether it has been in the well for only a few hours, or for ten years, the Baker Packer can be drilled up in minimum time. Expensive and hazardous "milling-out" operations never are required.

IMPORTANT FACTS

Baker Packers are used in a majority of installations where conditions of extreme pressure, temperature, or depth are present. Baker Packers also dominate Dual Zone installations, particularly those involving two-packer, crossed-flow arrangements.

BUT IT IS ALSO TRUE that *more* Baker Packers are used for *simple single zone* completions than for *any other type of completion*, and that *most* Baker Dual Zone installations employ *only one* packer.

Ask any Baker representative, or office, for complete details. There is no charge, and no obligation, for specific recommendations and completion planning advice available from Baker Technical Advisers. Why not be prepared for your next completion?

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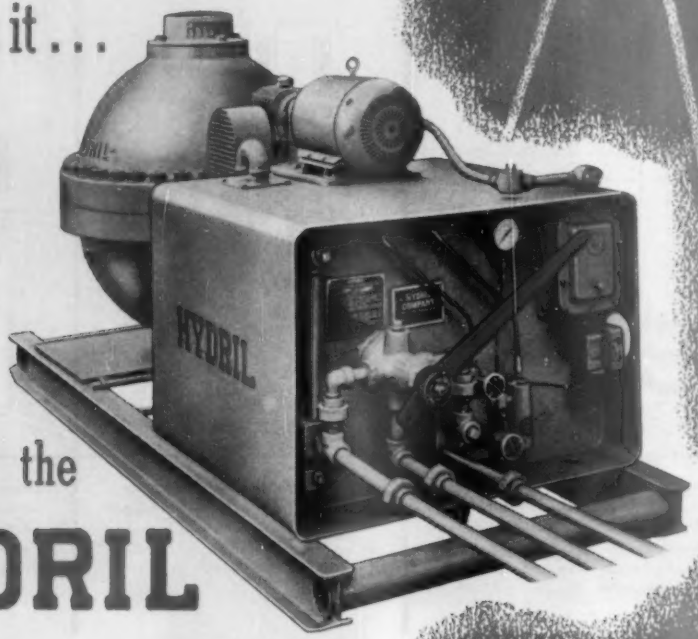
If your well is worth completing it's worth completing well

BAKER

RETAINER PRODUCTION PACKER

blowout prevention equipment is no better than the power available to operate it...



the

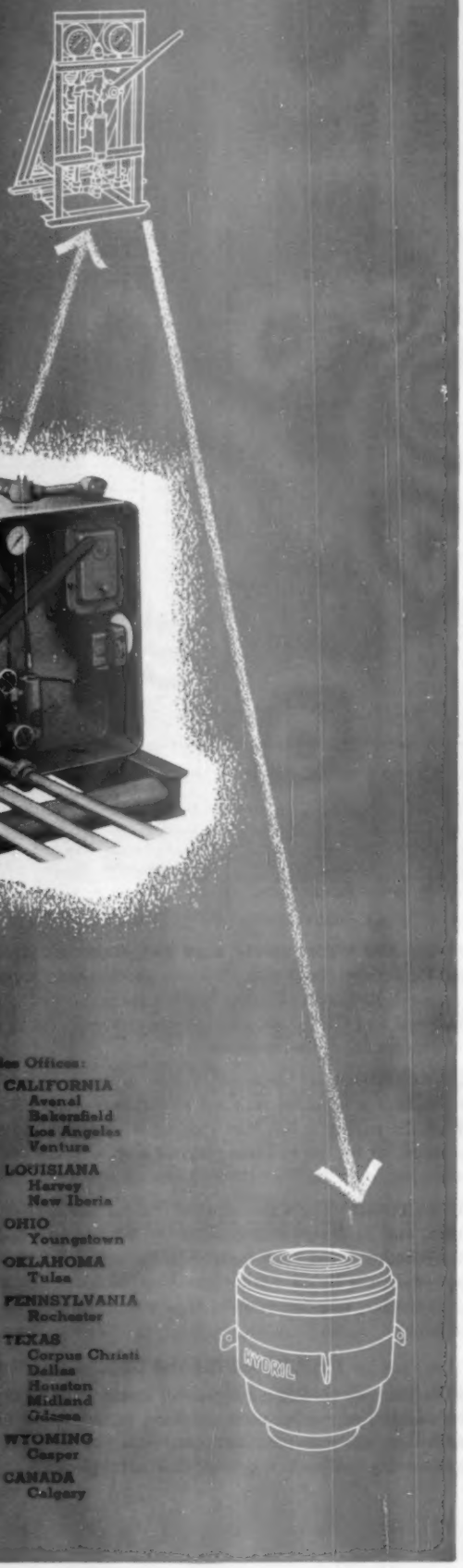
HYDRIL

automatic pump accumulator

...maintains a continuous, ample supply of hydraulic power for blowout preventer operation.

...stands ready for instant action the moment a blowout threatens.

...responds with unequalled speed...pressing a single lever applies the needed power at once... no lost time starting motors or pumps!



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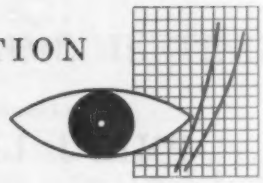
REPORT and INTERPRETATION



JOE B. ALFORD

EXECUTIVE SECRETARY
PETROLEUM BRANCH, AIME

Petroleum to be Added to Institute Name

The Petroleum Branch Executive Committee voted in San Antonio last October to submit a petition to the AIME Board of Directors that the name of the Institute be changed to American Institute of Mining, Metallurgical, and Petroleum Engineers, with the abbreviated name AIME to be retained. The petition was signed by members of the Branch Executive Committee and submitted to the Institute Board of Directors at the recent Annual Meeting in Chicago. It was accepted forthwith and approved unanimously by the Board, and this was followed by a considerable round of applause from numerous members from all Branches who were attending the meeting. It was evident that this change is definitely in order, and will be well received by the Institute at large.

Execution of this change requires an amendment to the AIME Constitution. The constitution is a brief document, consisting of only four Articles, setting forth the name, object, membership, directors, and amendments. The fourth article on procedures for amendments is almost as long as the other three combined. For interested members, the AIME Constitution and By-laws can be found in the last AIME membership directory published in January, 1953.

Proposed amendments to the constitution, after approval by the Institute Board of Directors, must be submitted to the entire membership for voting on them before Oct. 1 of any year. Return ballots will be received by the Institute Secretary until the second Tuesday in November, when they will be counted by tellers. The result of this count will be reported to the chairman of the next Institute Annual Meeting. Any members present in person at the Annual Meeting who have not voted on the amendments by ballot shall have the privilege of having their votes recorded before the result of the voting is announced. Any proposed amendment which shall have been accepted by a majority of the votes thus cast shall be adopted. Thus, the legal procedures for executing the name change will be carried out in the current year, and will be completed at the AIME Annual Meeting in New York in February, 1956.

AIME Local Section Organization and Finance

A part of the reorganization plan that established the three Branches in 1949 was the establishment of the AIME Council of Section Delegates. This body consisted of one delegate from each Institute Local Section to attend the AIME Annual Meeting in February of each year. It was intended as a means whereby each section could have at least one official representative at the Annual Meeting to express the section wishes at a meeting of the Council of Section Delegates. The Council is a deliberative body, which can make recommendations to the AIME Board of Directors, but cannot take final action with respect to section organization, operation, etc., within the Institute.

For the past few years, the annual meeting of the Council has been held on Saturday, preceding the opening of the Annual Meeting and the AIME Board of Directors meeting on Sunday. The Council has made several very good recommendations to the Board, and the presence of one delegate from each local section has unquestionably been of value to the Institute. Because of the wide diversity of interests between the sections and their delegates, however, the Council has spent a good bit of time in discussion that has been somewhat non-productive and ineffective. Coupled with this has been the rapid growth of Petroleum Branch representation through the formation of new sections, and the question of how "overlaying" petroleum sections should be represented. The net result has been that the Council of Section Delegates has become somewhat large and unwieldy, and considerable study has been done during the past year as to how its size might be reduced to a workable number.

Two primary proposals were made, one to have a Council of 20 members chosen on a rotating basis from the 10 AIME directoral districts, the other a Council of the same size but with representatives chosen by the three Branches on a membership ratio basis. After discussing them at the recent meeting in Chicago, the Council turned down both proposals, and voted to maintain itself on the basis of one delegate from each local section in the Institute, with travel expenses paid to the Annual Meeting. On this basis, the five so-called "overlaying" Petroleum sections would be placed on exactly the same status as all other sections and the term "overlaying" abolished. The AIME Board of Directors adopted this proposal by the Council, and thus set the Council of Section Delegates up to convene in 1956 on much the same basis as it was this year, but with a delegate from each section of the Institute.

Another recommendation made by the Council, and subsequently approved by the Board, was to continue section financing on the same basis as it was handled in 1954. This is a refund of 50 cents per member in each section, and 50 per cent of all money received from initiation fees. The number of members in each section to be used by the New York headquarters in making refunds to sections is shown on the Membership Page by Virginia B. Daggett on page 31 of this issue.

It is our understanding that travel expenses of section delegates to the 1956 Annual Meeting will be paid by the Institute. The system of making refunds of 50 per cent on all initiation fees has been changed this year in that the initiation fees for all changes of status will be included. The payment of initiation fees in installments does not affect the amount of refunds, as the Institute pays the full amount of half the fee to the Section on the first payment, regardless of how it is paid to the Institute by the member.

Favorable opinion was expressed at the meeting for the operation of sections along the lines agreed upon, and a good many members believe that the plans adopted will contribute to the growth of the Institute.

★★★

PHIL J. LEHNHARD . . . . . G. LATHAM YATES

Petroleum Branch

Vice-Chairmen

1955

Since he became field chairman of the East Texas Engineering Association in 1946, Phil J. Lehnhard has been a constant leader in all activities of the East Texas Local Section. He was elected program chairman in 1947; then, he was chosen: member of the board of directors, 1948 and 1949; local section chairman, 1950; member of the board of directors, 1951 and 1952; and again, program chairman, 1954. In 1955 he now steps up to the vice-chairmanship of the Petroleum Branch.

Phil graduated from the University of Oklahoma in 1931 with a BS degree in petroleum engineering. He started to work in Houston for Humble Oil and Refining Co. in 1932—first as a roustabout, then as a roughneck, and finally as a junior engineer. In 1935 he joined Dowell, Inc., in Tulsa, where he rose from his original position as "treating engineer" to the position of "research engineer." He continued his work with Dowell until 1944, serving as district engineer in the Mid-Continent, California, Gulf Coast, East Texas, and West Texas oil fields.

From 1944 to 1946 Phil was with United Oil Well Service, S.A., in Caracas, Venezuela. He joined the company during their organization period as research and development engineer, then served as chief engineer. He returned to Texas in 1946 to take over his present position in Kilgore with the East Texas Engineering Association.

Phil has been active as an author, having presented papers before two Petroleum Div. meetings. On the Austin meeting program in 1942 his paper was "Mud Acid — Its Theory and Application to Oil and Gas Wells." In 1944 he presented at a Houston meeting a paper later published in *Petroleum Transactions* entitled "Application of the Electric Pilot to Well Completion, Acidizing, and Production Problems in the Permian Basin."

Apart from his job of caring for the operation of the East Texas Engineering Association, Phil takes time to enjoy his favorite hobbies: fishing, shop work, photography, and keeping up with two teen-age daughters.

R. W. TAYLOR

A look at the college record of G. Latham Yates will indicate the well-rounded personality of the 1955 Petroleum Branch vice-chairman. In addition to earning money to finance his schooling by doing odd jobs, maintaining a B-plus average, and participating in varsity track and wrestling, Latham was an active member of:

Sigma Gamma Epsilon, honorary geological and petroleum engineering fraternity; Sigma Tau, honorary engineering fraternity; Sigma Xi, honorary research society; L.K.O.T., honorary engineering club; Toga, senior leadership society; Skeleton Key, senior honorary society; St. Pat's Council, student governing body of College of Engineering; Phi Club, sophomore honorary athletic club; Spiked Shoe Society, track club; Beta Theta Pi, social fraternity; and Men's Council, as College of Engineering representative.

He has continued this same type of energetic activity through the years — in his jobs and in professional organizations. Latham has been active in the Kansas Geological Society and the API, as well as the AIME. After serving as chairman of the Kansas Local Section, he was a member of the Petroleum Branch Executive Committee from 1952 through 1954. Now, he advances to the position of Branch vice-chairman.

After studying at Lehigh, Latham received both his BS and MS degrees from the University of Oklahoma. Shortly following his graduation in 1935 he became a member of the Dept. of Oil and Gas at the University of Pittsburgh. In 1943 he joined Kingwood Oil Co. in Effingham, Ill., for a short time; then, he moved to Standard Oil Co. of Ohio in Cleveland. He was head of the valuation engineering section of the Production Engineering Dept. of that company when he left in 1947 to open a consulting office. Since then, Latham has been a partner in the Wichita, Kan., consulting firm of Amstutz and Yates, Inc.

Amidst his active life in business and his service to the various professional societies, Latham enjoys a family life with his wife Marian and their three young children—Georgia Leslie, Julia Jane, and Jo Anne.

R. W. TAYLOR

BUSINESS DOMINATES ATTENTION at ANNUAL AIME MEETING

With the Petroleum Branch members in attendance at the AIME Annual Meeting being primarily members of the Board of Directors, the Executive Committee, Council of Section Delegates, and educators from the various university petroleum engineering departments, business meetings dominated the attention in Chicago Feb. 12-17.

The most important action taken at the meeting was the unanimous approval by the AIME Board of Directors of a proposal to change the name of the Institute to "American Institute of Mining, Metallurgical, and Petroleum Engineers." "Report and Interpretation" on page 25 of this issue gives complete details of this development.

Another topic which brought considerable discussion but no final action was a recommendation by the Committee of Five Presidents to move the site of the Engineering Societies Building to Pittsburgh. This recommendation was made by Leo F. Reinartz, 1954 AIME president, and presidents of four other "founder" societies. The Board voted to delay their final action until further consideration could be given by the members.

Houston in 1958

The Petroleum Branch Executive Committee voted to: (1) hold the 1958 Petroleum Branch Fall Meeting in Houston, (2) adopt rules for award and candidate selection procedure for the Cedric K. Ferguson Medal, (3) discontinue advance registration for Branch Fall Meetings, and (4) set up a committee to develop a program for attracting young men into the petroleum engineering profession.

The Council of Section Delegates voted down a proposal to reduce the number of delegates to two from each Directorial District. It requested the Board to: (1) continue to pay travel expenses of one representative from each local section, (2) continue to give sections the $10 rebate on initiation fees, and 50 cents to $1 rebate (depending upon the financial condition of the Institute) to each section for every member on its roles in good standing, and (3) change the boundaries of the Directorial Districts. M. B. Penn, Mid-Continent Petroleum Co., Tulsa, was chairman of the Council of Section Delegates.

The Educator's Conference framed a request to the Engineers Council for Professional Development that cognate curricula not be carried in the Council's listings. The educators feel it desirable that all curricula meeting the ECPD standards be listed alphabetically without division in the future. The problem leading to the discussions which lasted for two days in Chicago was brought about last fall when the ECPD, the accrediting society, classified petroleum engineering as a cognate or fringe curriculum, although the present requirements for a degree in petroleum engineering meet all the standards for full accreditation. Because of the cognate classification of petroleum engineering, the departments in various universities tend to receive less money than those which had received full accreditation from the ECPD.

A. W. Walker, University of Tulsa, was appointed to head a Committee to study problems concerning petroleum engineering education.

Donnell Speaks

The social highlight for Petroleum members was the Petroleum Branch Dinner held in the Conrad Hilton Hotel on the evening of Feb. 15. J. C. Donnell II, president of Ohio Oil Co., spoke to the 150 persons in attendance on "Engineers in Management." John R. McMillan, retiring Petroleum Branch chairman, presented the gavel to R. B. Gilmore, 1955 chairman, in an installation ceremony at the dinner.

The worldwide petroleum developments in 1954 were presented at the Annual Production Review Session on Feb. 14. Speakers were: A. H. Chapman, Arabian American; Milton Williams, Humble; A. H. Bell, Illinois Geological Survey; and Alfonso Barnetche, Petroleos Mexicanos. Forty-page preprints of the material presented are available upon request from the Petroleum Branch office.

The technical aspect of the program for Petroleum members included nine papers which were presented at three sessions. Abstracts of these papers were published in the January issue of JOURNAL OF PETROLEUM TECHNOLOGY.

New Officers

Petroleum Branch members assuming new offices at the meeting in addition to Gilmore were: R. W. French, Jr., Sohio Petroleum Co., Oklahoma City, and Howard C. Pyle, Monterey Oil Co., Los Angeles, who became members of the AIME Board of Directors; G. Latham Yates, Amstutz and Yates, Inc., Wichita, and Phil J. Lehnhard, East Texas Engineering Association, Kilgore, who took office as Petroleum Branch vice-chairmen; and George R. Gray, Baroid, Houston, Earl M. Kipp, The California Co., New Orleans, and John C. Calhoun, Pennsylvania State University, who became members of the Petroleum Branch Executive Committee. Calhoun is Mineral Industry Education Div. representative.

J. C. Donnell II, president of Ohio Oil Co., speaks at the Petroleum Branch Dinner. To the left of the speaker is John R. McMillan; to the right, L. S. Wescoat, past president and now chairman of the Executive Committee of The Pure Oil Co., Chicago, who introduced the speaker.

ERNEST O. KIRKENDALL

New AIME

Secretary

A registered professional engineer, doctor of science and former college professor has taken office as secretary of AIME. Efficient and genial Ernest O. Kirkendall moved into the position vacated by E. H. Robie, Institute secretary since 1949 who now becomes secretary emeritus following his many years of outstanding service.

Kirk is not new to the AIME—having been a dues paying member for many years before joining the staff in 1946. His name was prominent in the permanent literature as far back as 1939, when he wrote the first of a series of research papers on rates of diffusion of copper and zinc in alpha brass. Subsequent to this paper, published in *Transactions* volume 133, he wrote papers which were published in volumes 147 (1942) and 171 (1947).

Since joining the AIME staff as secretary of the Metals Branch in 1946, his successful work has gained the confidence of the Board of Directors. It was his record in that capacity which prompted the Board to select him for the important post of Institute secretary.

Kirk was named on Sept. 21, 1954, to succeed Robie, and at that time he was made administrative assistant to the Institute secretary. From then until he assumed the AIME secretaryship, he had an opportunity to work closely with the retiring secretary and learn the extent of his duties.

During this training period for his new job, Kirk visited the Petroleum Branch Fall Meeting in San Antonio last October. There he made many friends among the Petroleum members, and expressed a great admiration for the work of the Petroleum Branch. His appointment as AIME secretary pleased many Petroleum members who are acquainted with him.

Going into Kirk's background, we find that he was born in East Jordan, Mich., in 1914. In 1934 he received his BS in chemical engineering from Wayne University. He was awarded his MS degree in metallurgical engineering from the University of Michigan in 1935. In 1938 he received his DSc degree in metallurgical engineering from the University of Michigan.

He held a state fellowship at the University of Michigan in 1934-35. During college, Kirk was a member of Tau Beta Pi, Sigma Xi, Phi Lambda Upsilon, and Phi Kappa Phi, all honorary fraternities.

In 1937, prior to obtaining his DSc degree, he joined the Wayne University faculty as an instructor of metallurgical engineering. He became assistant professor in 1941, and served in that capacity at Wayne until joining the AIME staff in 1946. From 1938 until 1945, he was metallurgical consultant for Progressive Welder Co. of Detroit, along with his teaching duties at Wayne.

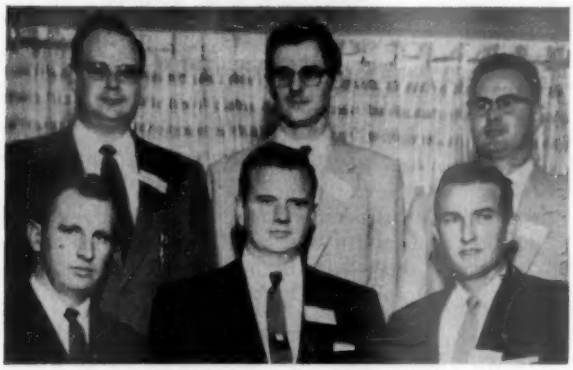
The Kirkendalls now reside in their home at 39 Howard Parkway, New Rochelle, N. Y. In addition to charming Mrs. Kirkendall, the family includes three children—daughters 9 and 16 years of age, and a son who is 14.

Kirk brings to the executive secretaryship of the AIME the quiet confidence of an experienced technical man. He knows engineering, and he is well acquainted with the operations of AIME after 10 years' experience. Kirk is felt by all who know him to be a worthy successor to the always dependable Ed Robie.

R. W. TAYLOR

Officers for 1955

PETROLEUM SECTIONS NAME NEW LEADERS



Outstanding event for the North Texas Local Section in 1954 was the Secondary Recovery Symposium in Wichita Falls which attracted 930 persons. Officers for 1955 are, back row left to right: David B. Meisenheimer, Texas Co., section delegate; Joseph Saxon, Jr., Ryder Scott Co., director; and J. W. W. Whitney, Jr., Magnolia, director. Pictured on the front row are: Fred Stephens, Cable Engineering, secretary; Elmer A. Milz, Shell; and A. J. Kerr, Lane-Wells. Milz was originally elected as 1955 chairman, but he was succeeded by Kerr, elected vice-chairman, when he was transferred to Tulsa. James A. Winfrey of Humble (not pictured) succeeds Kerr as vice-chairman. Another officer not pictured is Jack F. Berry, Texas Co., treasurer.

The Southwest Texas Local Section took in 60 new members and acted as host to the Petroleum Branch Fall Meeting in 1954. Now, 1955 officers have been elected. They are, on the back row reading left to right: Raymond Keller, Jr., J. B. Beard Co., director; George Wilson, Magnolia, director; Chester L. Wheless, La Gloria Oil & Gas Corp., past chairman and director; and J. M. Montgomery, Halliburton, director. On the front row are: R. J. Granberry, Core Laboratories, director; Fraser H. Allen, Stanolind, director; Robert R. Wallace, Seaboard, chairman; and C. L. Bramlett, Halliburton, director. Officers not shown in this photograph are: Ralph E. Warner, Seaboard, vice-chairman; and directors Pierre M. Aubuchon, La Gloria; Heath Renfro, Ralph E. Fair, Inc.; and R. G. Tonkin, Humble.

One of the newest Petroleum Branch local sections, the Hugoton Local Section, has elected officers for its second year of operation. Pictured on the back row, left to right, are: James C. Keaton, Hugoton Plains Gas & Oil Co., chairman; E. C. Kendall, McElroy Ranch Co., second vice-chairman; and W. H. Flood, Jr., Republic Natural Gas, director. On the front row are: C. P. Pyeatte, Republic Natural Gas, director; J. A. Jones, Panhandle Eastern Pipe Line Co., secretary-treasurer; and J. P. Phillippe, Panhandle Eastern Pipe Line Co., director. G. W. Atchley, Republic Natural Gas, vice-chairman, is not pictured.

The Illinois Basin Petroleum Section was formed in 1954 when the Illinois Basin Chapter voted to convert to local section status. New directors for 1955 for the section are, standing left to right: George K. Harcourt, Halliburton; William L. Robbins, Carter; and Bill G. Harmon, Di-Kor Coring Service. Officers seated are: George H. Link, Carter, second vice-chairman; Ray R. Vincent, C. L. McMahon, Inc., chairman; B. P. Walker, Gulf, first vice-chairman; and James T. Dorland, Calvert Drilling, Inc., secretary-treasurer.

Founded in 1954, the Panhandle Local Section quickly added 38 members to its original 25 and finished the year with a 152 per cent membership growth. Local section directors for 1955, standing left to right, are: Donald E. Radtke, Magnolia, past chairman; Robert W. Scarth, J. M. Huber Corp.; and Jack C. Bendler, Phillips. Officers seated, left to right, are: Donald W. Jackson, Gulf, secretary-treasurer; Henry J. Rose, Cabot Carbon Co., first vice-chairman; Joe M. Daniel, Jr., Texas Co., chairman; and W. O. Matejowsky, Schlumberger, second vice-chairman.

Mid-Continent Section Student Paper Contest Set for April 1-2 in Tulsa

Paul E. Fitzgerald, Dowell, Inc., chairman, is shown with several members of the Mid-Continent Section Student Paper Contest Committee. They are making plans for the contest which will be held on the campus of the University of Tulsa on April 1-2. Seated left to right are: A. W. Walker, professor of petroleum engineering at University of Tulsa; Chairman Fitzgerald; and Robert Marple, University of Tulsa student representative to AIME. Standing, left to right, are: Wayne Swearingen, liaison officer between University of Tulsa and AIME; R. C. Glover, Baker Oil Tools, housing; George R. Shaw, First National Bank & Trust Co., publicity; and Roy H. Smith, Stanolind, AIME liaison officer with University of Tulsa.

Papers entered in the contest will be divided between graduate and undergraduate papers, with students from the Universities of Tulsa, Oklahoma, Kansas, and Oklahoma A&M competing. Undergraduate papers will be heard on the afternoon of April 1; graduate papers being presented on the afternoon of April 2.

A dinner and smoker will be held in the University of Tulsa Student Union building on the evening of April 1. Saturday morning, April 2, a tour will be conducted through laboratories of a Tulsa oil company.

Prize-winning papers will be entered in the AIME National Student Paper Contest. Judges for the local contest have not been announced as yet. Mid-Continent Local Section members are urged to attend this student contest.

Nuclear Congress Planned

Engineers Joint Council is sponsoring a Nuclear Congress to be held in Cleveland Dec. 12-16, 1955. Most of the constituent societies of the EJC will take part, as well as others, notably the newly formed American Nuclear Society. An attendance of over 1,000 is expected. The Petroleum Branch Executive Committee has voted to send observers to this meeting, although the Branch will not take an active part in the program.

Mail coupon below for

INSTITUTE DIRECTORY TO BE PUBLISHED IN SPRING

An All-Institute Directory will be published by the AIME New York office in June. All members who wish to receive a copy of this Directory must fill out the coupon below and mail it to the New York office.

When filled out and returned, the coupon will serve as an address label for mailing the Directory; therefore, it is imperative that all who request the Directory use the coupon provided. Subsequent announcements will be made concerning the Directory, but the coupon appearing in this issue of the magazine will be the only valid requisition for the book.

Branch Directory in June

The Petroleum Branch will follow the practice it established last year of printing a separate directory of Petroleum Branch members as a bound-in supplement to the June issue of JOURNAL OF PETROLEUM TECHNOLOGY. However, Petroleum Branch members are eligible to receive the Institute Directory by sending in the coupon.

Names, positions, and addresses of all AIME members as carried on the master file cards of the Institute on Feb. 1, 1955, will be used in the Directory. Both an alphabetical and geographical listing will be included. The geographical listing will, as in the last Institute Directory, indicate which members are available for consulting work, and will also indicate the field of primary and subsidiary professional interests.

Supplement to Be Included

A supplement to the Directory containing a list of the officers, Branches, Divisions, local sections, committee personnel, and By-laws of the Institute will also be published — possibly as a part of the Directory.

Because of increased costs of producing the Directory, the AIME has adopted the practice now followed by the ASCE, ASME, AIEE, and AIChE of mailing the Directory only to those members in good standing who request it.

If you wish to receive the directory, print or type your name clearly on the coupon below which will be used as a mailing label, and send it to: AIME, 29 West 39th Street, New York, N. Y.

Send 1955 Directory to:

Name .....

Street Address .....

City ..... **State** .....

(Print Name and Address Clearly)

All Sections Have Chance in

1955 MEMBERSHIP CONTEST

VIRGINIA B. DAGGETT | *ASSISTANT SECRETARY PETROLEUM BRANCH, AIME*

For the past few years the Petroleum Branch membership contest has created a good deal of activity among the Petroleum local sections of AIME, resulting in a considerable number of applications for membership and substantial prizes to the winning local sections.

The contest has been based on percentage increase in membership, that is, applications received from a local section as a percentage of the section's membership on a given starting date. With a wide variance in the size of AIME local sections, the percentage method is fairer to the small sections than a contest based on number of new members, but we have realized that it is difficult for the larger sections to compete on this basis. This year, for example, the Hugoton Local Section, with a base membership of 27, could effect a 74 per cent increase with 20 new applications. The Gulf Coast Local Section, with 929 members, would have to secure 688 applications to meet this percentage.

In an effort to equalize the opportunities, petroleum sections this year will be placed in four groups, according to the size of base membership. Groupings of local sections and the base membership of each are shown below. Each section will be competing against other groups of the same relative size.

A prize will be awarded in each category for the largest percentage of applications. The winning sections will have a choice of a slide projector, a large banner, or $100 to apply on some other useful item which they desire.

All new and reinstatement applications for the three professional grades received in the Petroleum Branch office Jan. 1 through Dec. 31, 1955, will be eligible to count in the contest. Applications postmarked by midnight, Dec. 31, will be considered as received on that date. The base membership of each section, on which percentage increase is computed, is the number of members on record residing in that section as of Jan. 1, 1955.

Applications will be credited to the local section in whose territory the applicant resides, as determined by the address given on the face of the application.

Every member can help his section by talking AIME membership to friends and associates, and by suggesting the names of prospective members to his local section membership chairman. The Petroleum Branch office will gladly send application blanks and literature on AIME membership to interested and qualified persons upon request. We welcome the suggestions of members at all times.

SECTION GROUPS FOR 1955 PETROLEUM BRANCH MEMBERSHIP CONTEST

Group A — Section	Base Membership
Hugoton	27
South Plains	51
Mississippi	59
Panhandle	60
Billings	61
North Texas	84
Hobbs	88

Group B — Section	Base Membership
West Central Texas	135
Denver Petroleum	141
East Texas	141
Kansas	141
Lou-Ark	148
Wyoming	152
Illinois Basin Petroleum	154

Group C — Section	Base Membership
San Joaquin Valley	169
Fort Worth	181
New York Petroleum	212
Oklahoma City	269
Delta	308
Permian Basin	352

Group D — Section	Base Membership
Dallas	433
Southwest Texas	461
Mid-Continent	553
Southern California Petroleum	597
Gulf Coast	929

Proposed for Membership, Petroleum Branch, AIME

TOTAL AIME membership on Dec. 31, 1954, was 21,816; in addition 2,179 Student Associates were enrolled.

PETROLEUM BRANCH ADMISSIONS COMMITTEE

Virgil B. Harris, chairman; C. C. Harter; Charles Hudson; Raoul J. Bethancourt; Oscar K. McElheney; Jack Wahl.

INSTITUTE ADMISSIONS COMMITTEE

P. D. Wilson, chairman; F. A. Ayer; A. C. Brinker; R. H. Dickson; T. D. Jones; F. T. Hanson; Sidney Rolle; O. B. J. Fraser; F. T. Sisco; Frank T. Weems; R. L. Ziegfeld; R. B. Caples; F. W. McQuiston, Jr.; Arthur R. Lytle; H. R. Wheeler; L. P. Warriner; J. H. Scaff.

The Institute desires to extend its privileges to every person to whom it can be of service, but does not desire as members persons who are unqualified. Institute members are urged to review this list as soon as possible and immediately to inform the Secretary's office if names of people are found who are known to be unqualified for AIME membership.

In the following list C/ means change of status; R, reinstatement; M, Members; J, Junior Member; A, Associate Member; S, Student Associate.

California

Bakersfield—Cameron, Thomas William (M).
Brea—Stegemeier, Richard Joseph (J).
Downey—Godfrey, William Kerr (C/S-A-M).
Hollywood—Rodriguez, Sergio Enrique (J).
Los Angeles—Grant, Charles Dick (A).
San Francisco — Ambler, Richard Hayward (J).
Santa Maria—McCullough, Joe Jackson (C/S-A-M).
Santa Paula—Lester, Graham Wallace (C/S-A-M).
South Gate—Parsons, William K. (M).
Taft—Eyraud, Louis Ernest (M).
Whittier—Suter, Vane Edward (R, C/S-S-J).

Colorado

Colorado Springs — Wilson, Charles Vernon (M).
Rangely—Hill, Joseph Philip (J).

Illinois

Carmi—Keyes, William Oliver (J).
Olney—Jones, Frank T. (C/S-A-M).

Kansas

Chase—Taylor, Marlin R. (J)
Hays—Klein, Marvin LaNorris (M).
Liberal—Curry, James Kenneth (M); Ford, John Daniel (C/S-A-M).
Thrall—Hull, Winfield Scott (M).

Mississippi

Heidelberg—DeBord, George Edward (J).

New Mexico

Hobbs—Farmer, William Samuel (M); Turner, James Edward (J).
Santa Fe—Rhodes, Harlan Newell (J).

Oklahoma

Bartlesville—Chin, Tim (J); Corliss, Earl Robert (J); McGhee, Vernon Thomas (C/S-A-M); Miller, John Swanson (J).
Drumright—Morris, Joseph Alfred (C/S-A-M).
Duncan—Ostroot, G. Warren (M).
Oklahoma City—Dowds, John Potter (J); Hopcraft, Calvin Phillip (A).
Ponca City—Conley, Francis Raymond (M); Spencer, John Raymond (C/S-A-M).
Shidler—Holladay, John Milton (J).
Tulsa — Evans, Robert Buckner, III (J); Smith, Marion R. (C/S-A-M).

Texas

Abilene—Hunter, Hassell Eugene (M).
Alvin—Hogan, Charles Ira (J).
Amarillo — Knight, Orland (Jack) Lenard (M).
Beaumont—Biscamp, Roy Gene (R, C/S-S-A).
Bellaire—Hill, Harold J. (M); Suder, Floyd Eugene, Jr. (C/S-A-M).
Borger—Smith, David Earl (J).
Brownfield—Randle, Robert Curtis (C/S-A-M).
Corpus Christi — Obenhaus, Gus Faber, Jr. (M).
Dallas—Bright, Harvey Roberts (M); Hollabaugh, George Ryst (J); Koepf, Ernest Henry (R, M); McDonal, Frank J. (M); Stewart, Gladstone, Jr. (M); Williams, Gordon Bullitt (M).
Delmita—Morgan, Jack Allen (R, C/S-S-M).
El Paso—Williams, Thomas Jefferson (M).
Fort Worth—Bowersock, Dale D. (M); Krath, Jay Ennis (J); Richards, Warren Ball (J).
Hawkins—Lawless, Joe Lynn (J).
Houston—Andrew, Norman Keats (M); Chapman, Peter Frank (C/S-A-M); Davis, Benjamin Franklin (M); Gant, Guy William (A); Griffin, James Stephen (M); Kraemer, M. Scott (C/S-A-M); Newlin, Floyd Koenig (M); Newman, John Ames (C/S-A-M); Schell, James Hays (M); Wagenecht, Eugene Gail (J); Widner, George Washburn (C/S-A-M).
Kilgore—Happel, Philip E. (J).
Midland—Bachman, William Sherrod (C/S-A-M); Bruno, Earl Randolph (M); Cocnower, Robert Dunlavy (M); Thurman, Earl Grover, Jr. (C/S-A-M).
Odessa—Cross, Jonathan Henry, Jr. (R, C/S-S-J); Kading, Horace Wayne (A).
Pampa—Osborne, Edwin Forrest, Jr. (A); White, Leonard Lawrence (M).
San Antonio—Winslow, Harry Clark, Jr. (A).
Tyler—Pownell, Galyn Dee (J).
Uvalde—Karpos, George Toney (R, C/S-S-J).

Wyoming

Casper—Fraher, John Albert (C/S-A-M).

Venezuela

Caracas—Chatas, Angelos Thomas (C/S-A-M).

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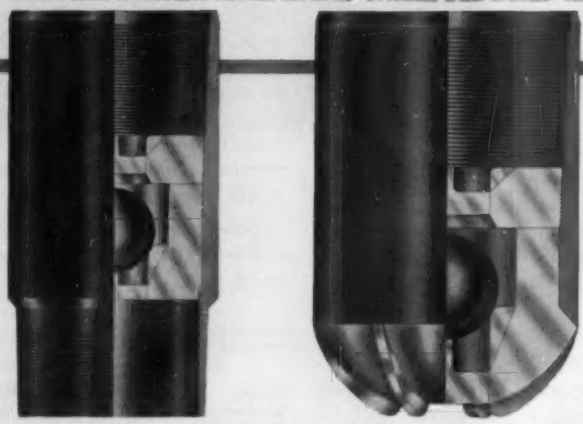

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New York Petroleum Section Hears Petrochemical Talk

"In 1955 the output of the petrochemical industry may be four or five times as great as in 1939. The total assets of the petrochemical industry are now valued at over three billion dollars."

This information was given at a recent meeting of the New York Petroleum Section by H. G. McGrath, associate manager of M. W. Kellogg Co., a Pullman, Inc., subsidiary. He stated that petrochemicals now account for about 25 per cent of our total chemical production, and that in less than 10 years they will account for 50 per cent.

"The opportunities for growth are enormous and are expanding at such a rate as to assure an even more rapidly expanding industry in the future," he said.

After discussing the various classes of petrochemicals, McGrath pointed out that the discovery of hydrogen synthesis by Fischer and Tropsch is one of the most significant contributions in the field of chemistry in the last generation. This allows the synthesis of many organic compounds through the interaction of hydrogen and carbon monoxide.

The greatest outlet for petrochemicals is being brought about by the gasoline octane race in the petroleum industry, he said. Use of chemical compounds to obtain a superior quality product is increasing rapidly.

Permian Section Publishes Water Resistivities Book

A booklet entitled "A Survey of Resistivities of Water from Subsurface Formations in West Texas" has been published by the Permian Basin Local Section in cooperation with Schlumberger Well Surveying Corp. Copies of the booklet may be obtained for $1.50 by writing to: AIME, P. O. Box 1858, Midland, Tex.

The compilation of the statistics was done by the West Texas Resistivity Sub-Committee. W. L. Carothers, of Humble, is chairman of this Committee. Members are: S. H. Rockwood, Shell; William Caffey, Standard Oil of Texas; C. F. Qualia, Sinclair; G. J. Decker, Schlumberger; Fred S. Wright, Jr., Magnolia; Phil Tomlinson, Atlantic; Phil Bridges, Stanolind; Robert Shields, The Texas Co.; Walter Baird, Gulf; and John R. Brack, Forest Oil Co.

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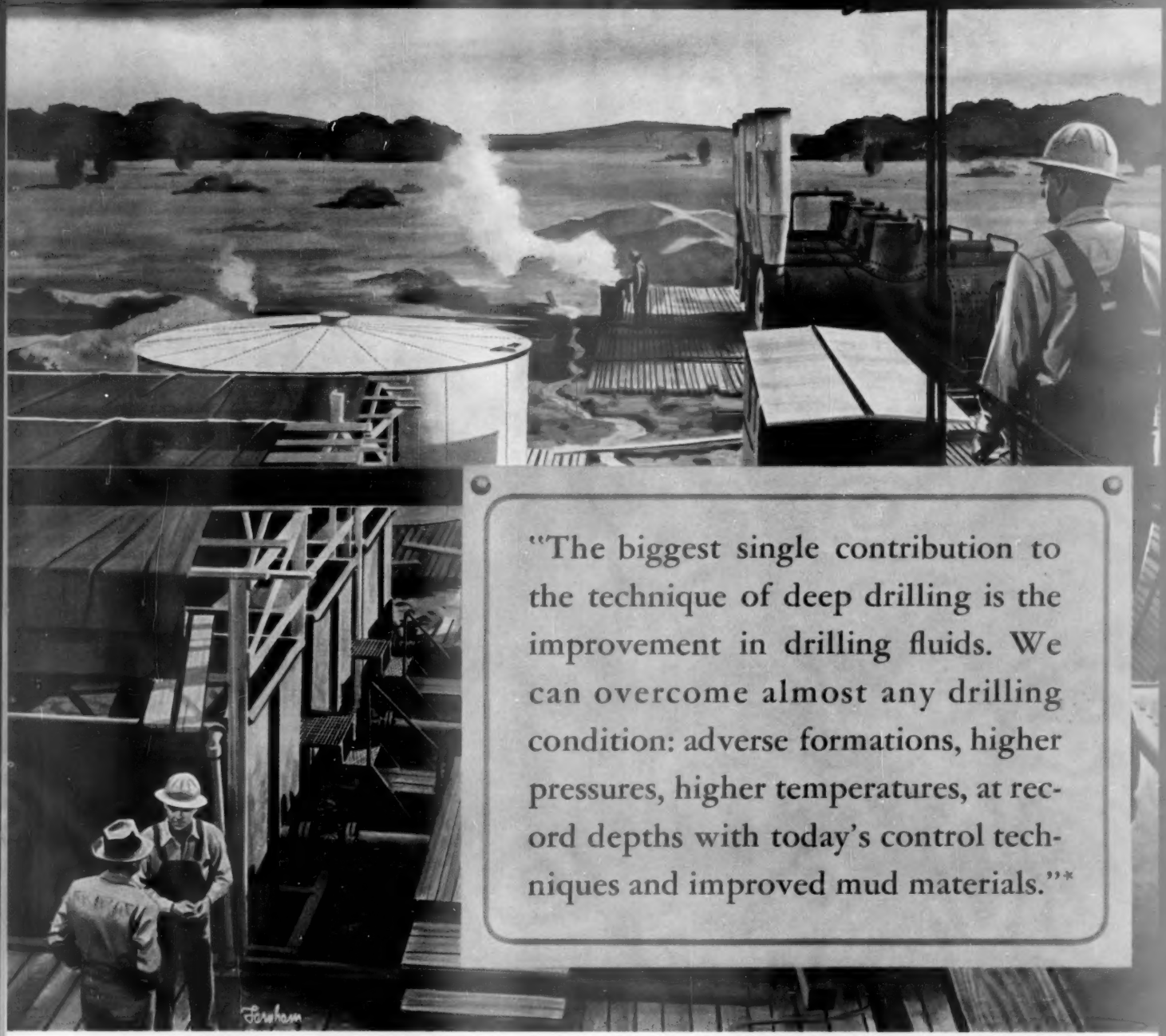

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*Combined opinion of seven drilling industry leaders answering a survey by *The Drilling Contractor*, Aug., 1952

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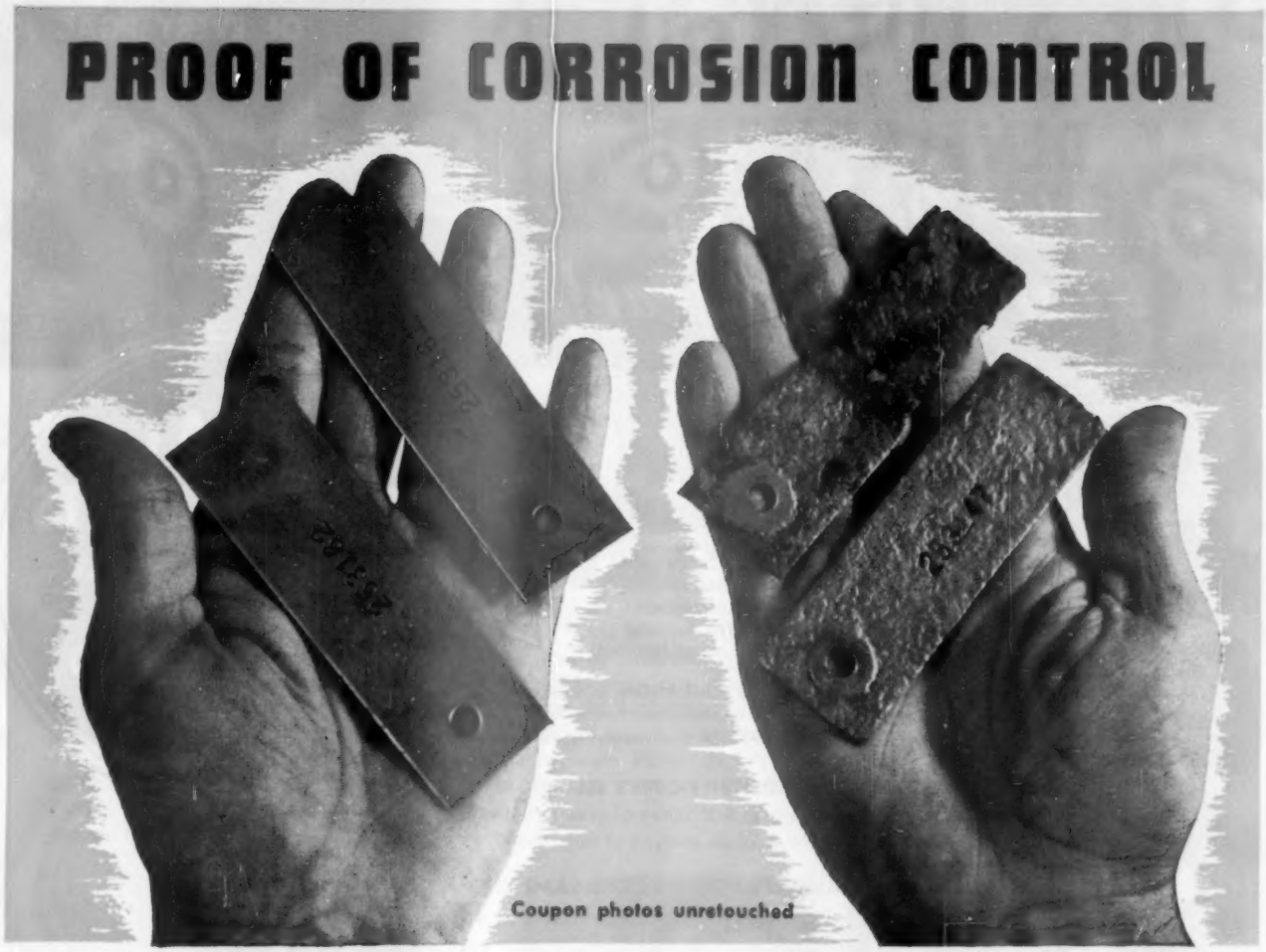

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*1 mil=.001 inch. A corrosion rate of 216 mils per year means that the corrosive attack, if uniform, would have corroded away the entire surface of the metal to a depth of .216 inches in a year. However, the real danger of high corrosion rates, as the coupon shows, is the much deeper and faster penetration occurring at localized areas.

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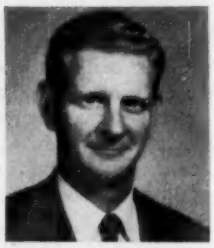

ROBERT C. RUMBLE is a research engineer for Humble Oil & Refining Co., Houston. He received a BS degree from Texas A&I and completed a year of graduate work at the University of Texas. After six years with the International Petroleum Co. as geophysicist in South America and 1½ years with Western Electric Co. as field engineer attached to the Air Force, he joined the Production Research Division of Humble in 1945.

DAVID CORNELL has since 1952 been assistant professor of chemical engineering at the University of Texas. He holds BS and MS degrees in chemical engineering from the University of Michigan and a PhD degree from the University of Texas. He has worked for 1½ summers with Texas Petroleum Research Committee and for two years with the Blaw-Knox Co.

G. A. CROES joined Koninklijke/Shell-Laboratorium, Amsterdam, immediately after graduation from the University of Groningen (Netherlands) in 1951. He has worked primarily on the theoretical aspects of various problems in the field of oil production research.

YUSUF K. SUKKAR received his BA in chemistry from American University of Beirut, Lebanon, in 1951. He has received his MS degree in chemical engineering from the University of Texas and is now working towards his PhD. For the academic years of 1953-54 and 1954-55 he has been awarded the Gulf Corp. fellowship.

N. SCHWARZ, a graduate of the Technical University of Delft (Netherlands), is leader of a reservoir engineering research group at Koninklijke/Shell-Laboratorium, Amsterdam. He joined Shell in 1949 and began research work on crude oil dehydration and mechanics.

D. L. GARTHWAITE, senior petroleum engineer with Stanolind Oil and Gas Co., received his BS degree in mechanical engineering from the

(Continued on Page 47)

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PERSONNEL AVAILABLE

☆ Petroleum Engineer, BS, University of Oklahoma, age 24, will complete military service in March 1955, married, one child. Desires position with major or independent oil company. Locate within U. S. Code 236.

☆ Petroleum Geologist, presently employed in responsible position Gulf South. Age 37, married. Eleven years' experience, reserve estimates, property evaluation, subsurface exploration, secondary recovery engineering, and geological consulting work. Desires association in New York City or northeastern states with organization or individuals having petroleum or mineral interests. Code 237.

☆ Petroleum Engineer, graduate of Texas A&M, 27 years old, married. Four years' experience in rig and reservoir work. Desires position with independent oil company. Presently employed. Code 238.

☆ Petroleum Engineer, 30, registered in Texas with seven years' varied exploitation and production experience. Thoroughly trained in reservoir engineering and production geology, with major company six years. Now with independent company but desires change. Married, two children. Code 239.

☆ Graduate with BS degree in petroleum engineering and BA degree in mathematics, interested in reservoir engineering, desires position with oil company. One year's experience in the field. Married, 26, writes and speaks fluently Arabic and French. Now employed. Code 240.

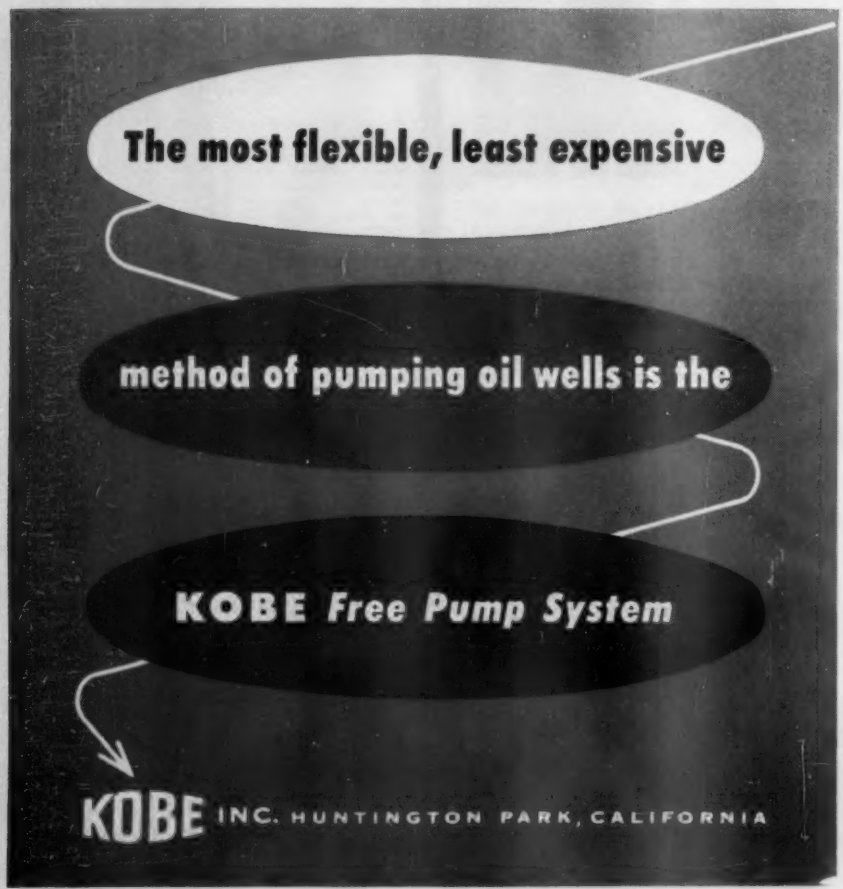
☆ Petroleum Engineer, 29, with five years' experience in drilling, production, and reservoir engineering. Currently employed with independent oil company. Prefers to work in West Texas-New Mexico area. Code 241.

☆ Reservoir Engineer, MS degree and four years' experience in reservoir valuation and secondary recovery programs. Now employed with major company. Code 242.

☆ Graduate Petroleum Engineer, 36, married, registered in Texas, desires position with independent oil producer in Midland, Tex., that requires initiative, resourcefulness, and hard work. Two years' drilling and four years' production experience. Presently employed. Code 243.

POSITIONS OPEN

☆ Petroleum Engineer, with MS or PhD in chemistry, mechanical or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☆ Major Oil Company has openings in New York City and in its foreign operations for graduate petroleum engineers with experience, and for recent graduates in this field to perform engineering work in development, production, drilling, process and oil and gas engineering on primary and secondary recovery. Write giving full particulars regarding personal history and work experience. Code 573.

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☆ Research Engineer. Major oil research company has opening for PhD or MS with minimum of three years' research experience in the field of reservoir mechanics. Opportunity for original work. Send detailed education and experience record, age, and state salary expected. Code 579.

(Continued on Page 47)

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Statistics Preprint Offered

A 40-page preprint entitled Summary of Oil and Gas Development and Production in 1954 is available free-of-charge from the Petroleum Branch office, 800 Fidelity Union Bldg., Dallas. The material in this preprint was presented at the Annual Production Review Session on Feb. 14 during the AIME Annual Meeting. Covered in this booklet are reports on the United States, Canada, South America, Europe, Far East, and Middle East. ★★★

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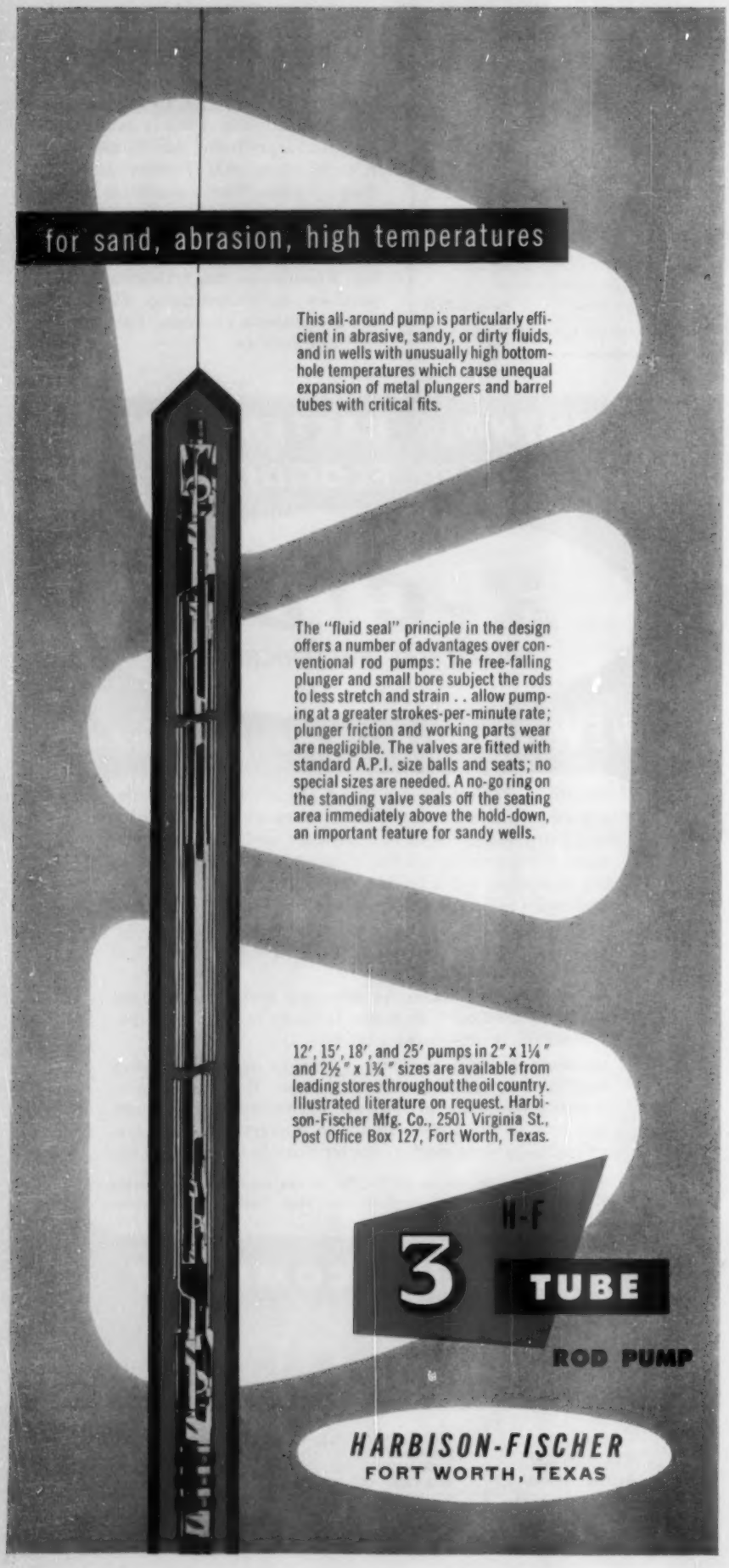
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PERSONALS

WILLIAM B. (BEN) ADAIR has been promoted to chief engineer of Macco Oil Tool Co. He will remain as chief sales engineer of the Houston Division of Macco, a position he has held since March, 1954. The petroleum engineering graduate of Texas A&M worked with Associated Engineers in Houston prior to joining Macco in Feb., 1953.

★

FRED H. POETTMANN will be the engineering supervisor for The Ohio Oil Co.'s Research Laboratory to be located near Denver. Before joining The Ohio in January, he had worked for the American Gas Association and Lubrizol Corp., the Phillips Petroleum Co., and Oklahoma A&M College. Born in Germany, Poettmann studied in the United States at Case Institute of Technology and received his ScD degree in chemical engineering from the University of Michigan.

★

E. W. BERLIN has been appointed general representative of Socony-Vacuum's operating subsidiaries in Indonesia. Stationed at Djakarta, he will have administrative supervision over Stanvac's exploration, producing, refining, marine, and pipeline transportation, and sales activities in the Indonesian republic. He has had 29 years of experience in the petroleum industry, 26 of which have been in the international field.

★

ROGER C. HAMEL, JR., is now vice-president of the Victoria Bank & Trust Co. of Victoria, Tex. He is in charge of the Oil and Gas Dept.,

oil property evaluation, oil loans, and loan servicing. He has been with Humble for the past eight years, having served for the past 2½ years as district petroleum engineer at Brookhaven, Miss.

★

WARNER M. KELLY has been named South Texas division manager for Otis Pressure Control, Inc. He has been with Otis for 10 years, serving most recently as Caliper Dept. division manager of South Texas. Prior to joining Otis he was with Edwards Drilling Co. and Pan-American Production Co.

★

JOHN J. JUSTEN is now with Socony-Vacuum Oil Co. of Canada on a special assignment. His office is located in the Barron Building, Calgary, Alberta. Justen was working with Magnolia Petroleum Co. in Dallas prior to receiving this special assignment.

★

COLIN C. RAE has retired from active work as assistant to the president of Skelly Oil Co. He has been engaged for 42 years as geologist, petroleum engineer, and executive for various oil companies and U.S. Geological Survey in California, Wyoming, and Mid-Continent areas. He contributed to the discovery of gas and later oil in the Big Sand Draw field, Wyo. The AIME member since 1920 now has plans for travel and recreation.

★

GORDON H. FISHER is now vice-president in charge of all field operations of Plymouth Oil Co. with offices located in Sinton, Tex. Prior to accepting this position he was assistant to the vice-president for exploitation of Gulf Oil Corp., Fort Worth. Fisher is a past local section chairman and in 1948 was chairman of the Branch Publications Committee.

Local Section Meeting Schedule

Petroleum Branch records indicate that the men listed below as chairmen are either newly-elected for 1955 or are serving unexpired terms after being elected in 1954. When available, the normal meeting date of each section predominantly petroleum in membership is listed.

The Branch office would appreciate receiving any additions or corrections to this list, so that all chairmen may be listed correctly and normal meeting dates may be published for each local section in future publications.

BILLINGS PETROLEUM SECTION: Meets in Billings, Mont. *Chairman*, Charles F. Hunkins, Northern Pacific Railway, Billings.

DALLAS SECTION: Meets third Monday each month in Dallas. *Chairman*, R. F. Modera, Republic Natural Gas Co., Dallas.

DELTA SECTION: Meets second Tuesday each month in New Orleans. *Chairman*, B. L. Francis, Texas Co., New Orleans.

DENVER PETROLEUM SECTION: *Chairman*, Robert Hass, Midwest Oil Corp., Denver.

EAST TEXAS SECTION: Meets second Tuesday each month at Gregg County Airport. *Chairman*, John Calvert, Humble, Tyler.

FORT WORTH SECTION: Meets third Tuesday each month in Fort Worth. *Chairman*, Lewis H. Bond, Jr., Fort Worth National Bank, Fort Worth.

GULF COAST SECTION: Meets third Tuesday each month in Houston. *Chairman*, Ray A. Bobo, Phillips, Houston.

HOBBS PETROLEUM SECTION: Meets in Hobbs, N. M. *Chairman*, H. P. Shackelford, Tidewater Associated Oil Co., Hobbs.

HUGOTON LOCAL SECTION: Meets in Liberal, Kans., and Guymon, Okla. *Chairman*, James C. Keaton, Hugoton Plains Gas & Oil Co., Hooker, Okla.

ILLINOIS PETROLEUM SECTION: Meets first Thursday each month in Salem, Ill. (No meetings in July and August.) *Chairman*, Ray R. Vincent, C. L. McMahon, Inc., Evansville, Ind.

KANSAS SECTION: Meets second Wednesday in Wichita and fourth Thursday in Great Bend. (No meetings in June, July, and August.) *Chairman*, James R. Paul, Dowell, Wichita.

LOU-ARK SECTION: Meets third Monday each month in Shreveport, La. *Chairman*, B. F. Patterson, Jr., Texas Co., Shreveport.

MID-CONTINENT SECTION: Meets second Monday each month in Tulsa; study group meets fourth Tuesday each month. (Luncheon meetings each Thursday, Mayo Hotel.) *Chairman*, M. B. Penn, Mid-Continent Petroleum Co., Tulsa.

MISSISSIPPI SECTION: Meets in Laurel, Jackson, and Natchez, Miss. *Chairman*, E. J. Grady, Gulf Refining Co., Natchez.

NEW YORK PETROLEUM SECTION: Meets in New York City monthly. *Chairman*, H. E. McAuliffe, Jr., Socony-Vacuum Co., New York City.

NORTH TEXAS SECTION: Meets second Monday each month in Wichita Falls. *Chairman*, A. J. Kerr, Lane-Wells, Wichita Falls.

OKLAHOMA CITY SECTION: Meets at noon third Thursday each month in Oklahoma City. *Chairman*, R. K. McIver, Consultant, Oklahoma City.

PANHANDLE LOCAL SECTION: Meets in Pampa, Tex. *Chairman*, Joe M. Daniel, Jr., Texas Co., Pampa.

PERMIAN BASIN SECTION: Meets third Monday each month in Midland or Odessa, Tex. Chairman, A. L. Carpenter, Humble, Odessa.

SAN JOAQUIN VALLEY SECTION: Meets first Tuesday alternate months (February-December) in Bakersfield, Calif. *Chairman*, C. A. Davis, Richfield Oil Corp., New Cuyama, Calif.

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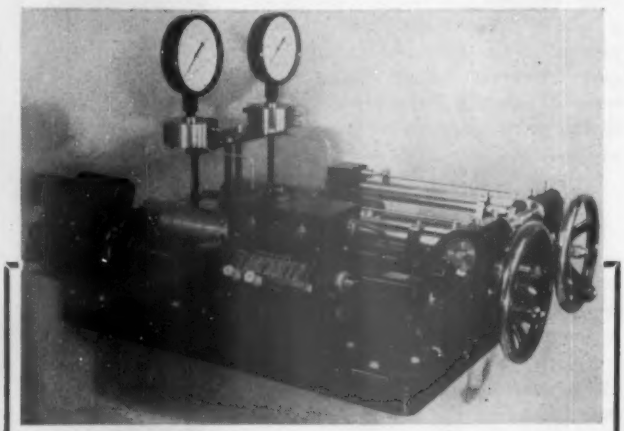

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Missouri School of Mines in 1948. He joined Stanolind after graduation and is currently employed in the reservoir engineering section of the Casper Div. office.

F. K. KREBILL is the reservoir engineering section leader with Stanolind Oil and Gas Co., in the Cody, Wyo., district office. He received his BS degree in mechanical engineering from Colorado A&M in 1948. Since that time, he worked in the Elk Basin and Rangely fields prior to his transfer to Cody in 1952. A photograph and biographical sketch of F. M. STEWART appeared in the Sept., 1954, issue of the JOURNAL OF PETROLEUM TECHNOLOGY.

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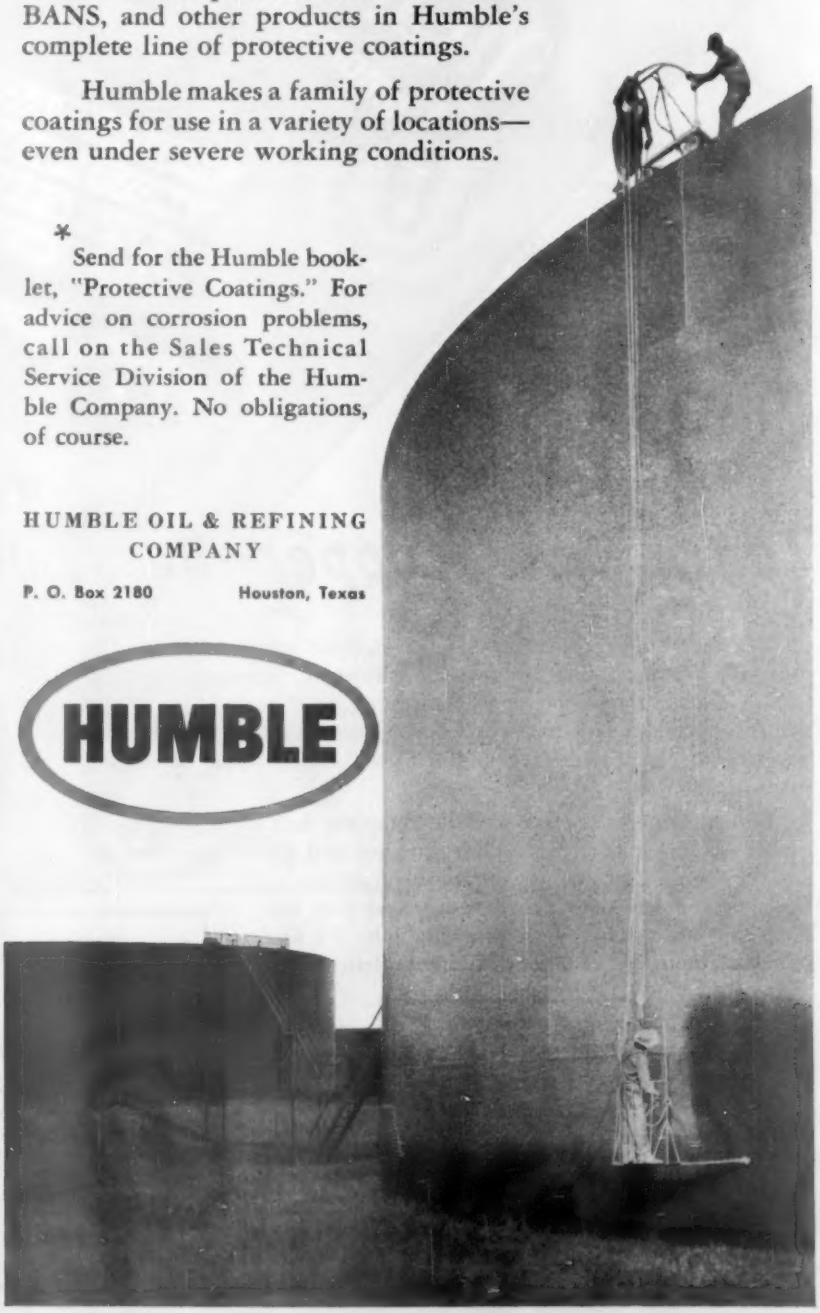

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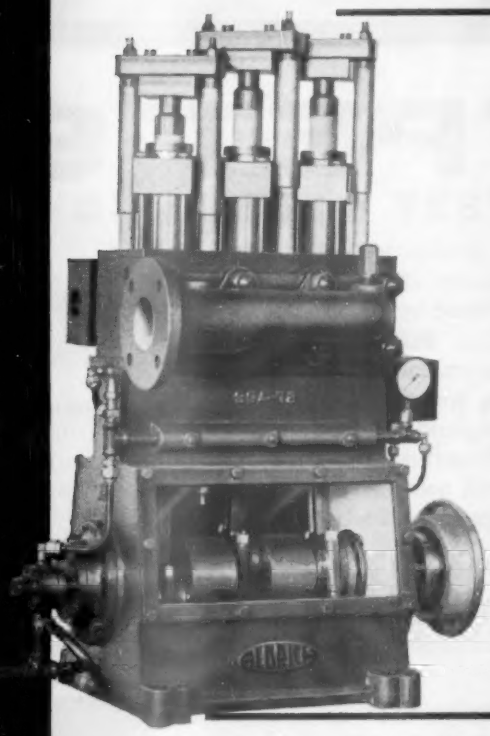

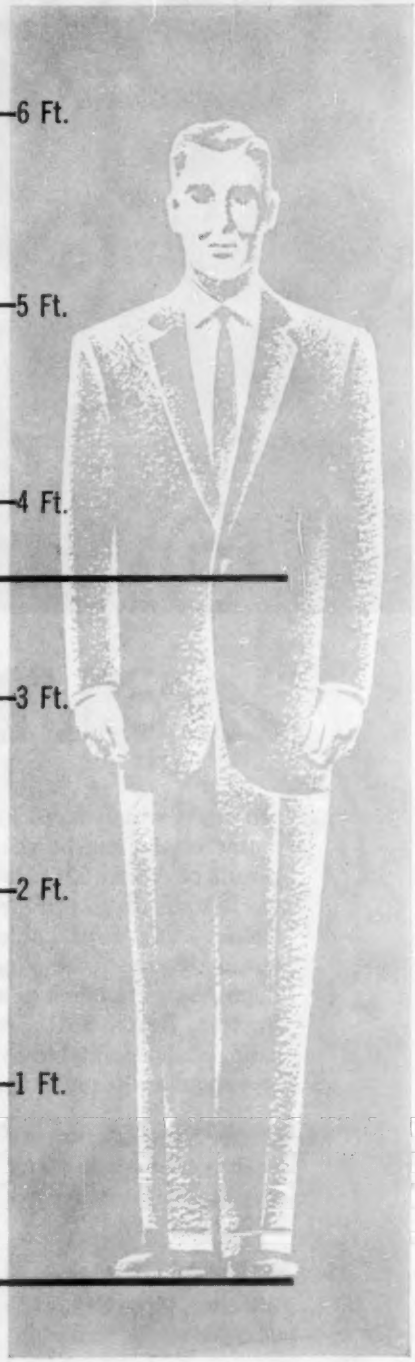

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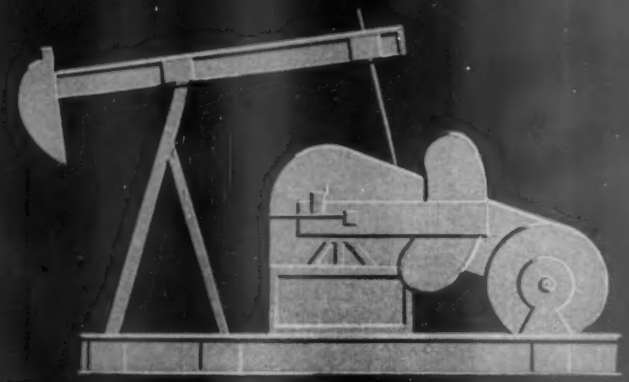

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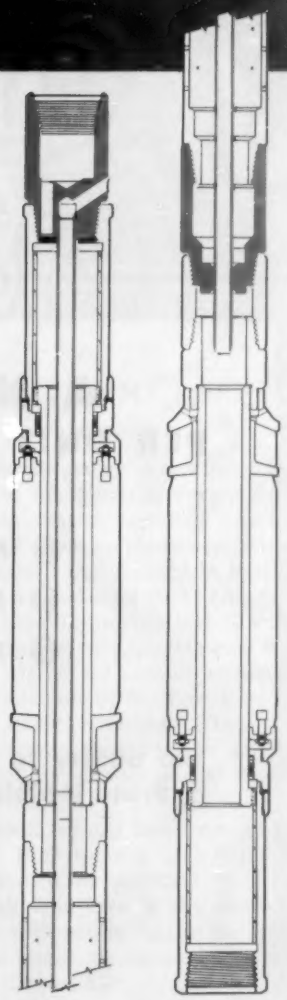

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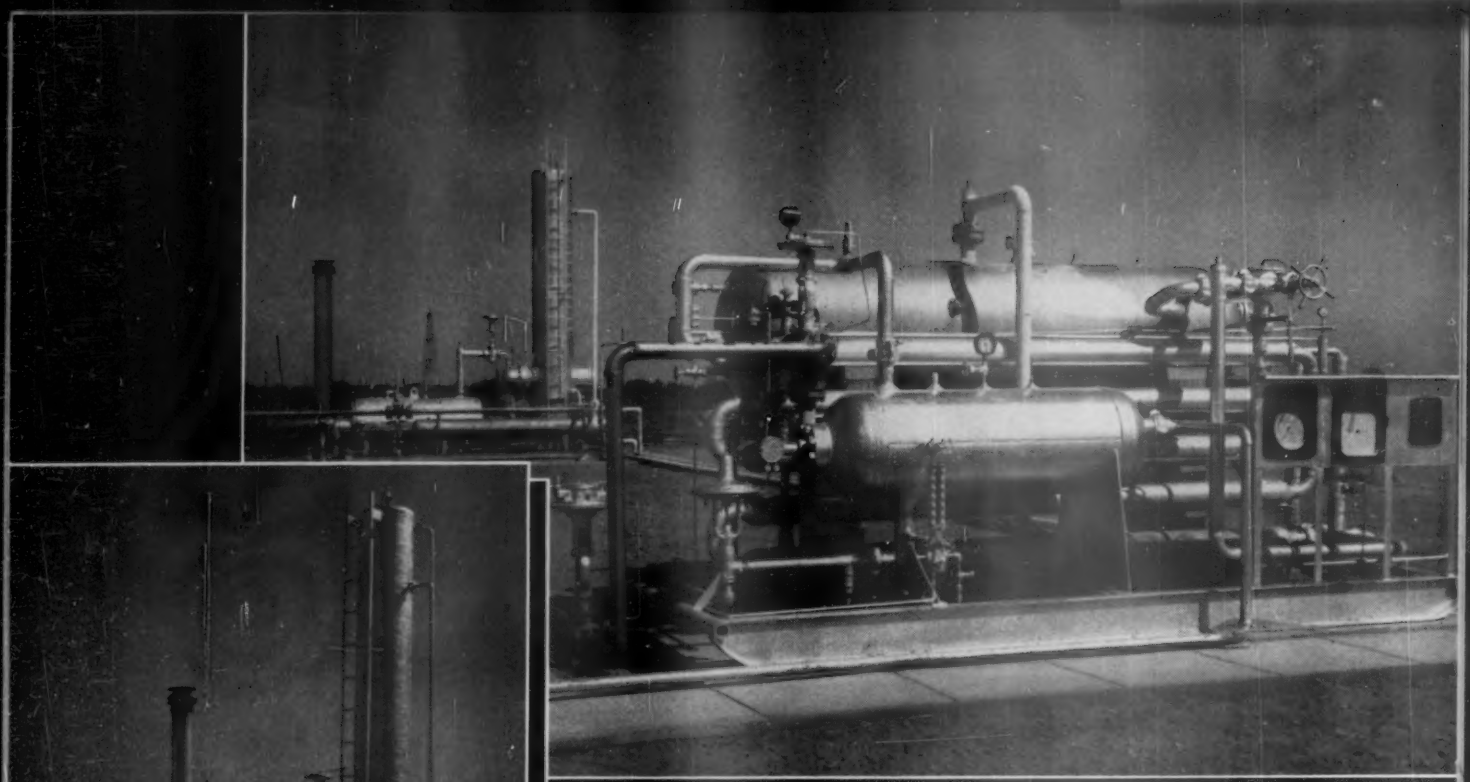

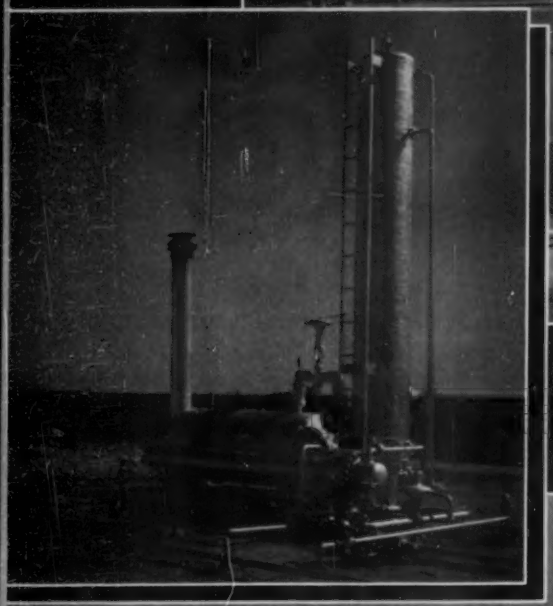

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A SUBSURFACE FLOWMETER

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ABSTRACT

To meet the need for a subsurface flowmeter capable of measuring low rates of flow, a new type flowmeter has been built and tested in the field. This instrument is self-contained, can be run on a wire measuring line, and may be run through 2-in tubing. It consists of a rotameter flow-measuring assembly used in conjunction with a conventional subsurface instrument clock and chart. Integral with the tool is an inflatable packer which, by effecting a seal between casing and tool, diverts all fluid through the metering assembly. Packers of different size adapt the tool to different sizes of casing or liner. The flowmeter is capable of measuring rates of flow as low as 4 B/D.

The flowmeter has been run experimentally in seven wells. It has yielded satisfactory results in five of the wells, and in the other two it failed to operate because of loose sand in the hole.

INTRODUCTION

One of the oldest problems facing the producing branch of the petroleum industry is the location of depths of entry of fluid into a wellbore and the determination of the amount of fluid entering at each depth. This problem is often encountered in oil and gas wells completed in single producing horizons as well as in multiple pays; it is a common problem in oil wells which produce excessive volumes of gas.

Several subsurface instruments designed to detect and meter flow in the producing interval of wells have been described in the literature.[1,2,3,4] Most of these, however, were apparently intended for use in wells producing at relatively high rates of flow, and consequently lack sensitivity to low flow rates. Because of this and of other possible disadvantages inherent in these instruments, development of the subsurface flowmeter described in this report was undertaken.

DESIGN OF FLOWMETER

Design Requirements

In considering the requirements for a flowmeter that would not be subject to the limitations of devices existing at the time work was started, attention was first given to the size of the tool. Such an instrument should be of sufficiently small diameter that it could be lowered readily in 2-in tubing in a producing well. The flowmeter should contain a recording unit so that it might be run on a wire measuring line with conventional reeling equipment. It should not be too long to be accommodated by a portable lubricator of the type used for running conventional subsurface instruments. The metering mechanism of the flowmeter should not be affected appreciably by the viscosity or density of the flowing fluid.

Such an instrument should record flow rates in the range from less than 10 B/D to over 100 B/D. To achieve this, a packer should be provided to divert through the instrument all fluid flow in the wellbore. This packer should be of such nature that in the event of excessive flow the fluid would bypass the instrument instead of forcing it up the wellbore.

General Description

A flowmeter incorporating most of the desired features outlined above was developed and built. The instrument is an elongated tubular device terminated on

Manuscript received in Petroleum Branch office on Sept. 10, 1954. Paper presented at Petroleum Branch Fall Meeting in San Antonio, Oct. 17-20, 1954.

[1]References given at end of paper.

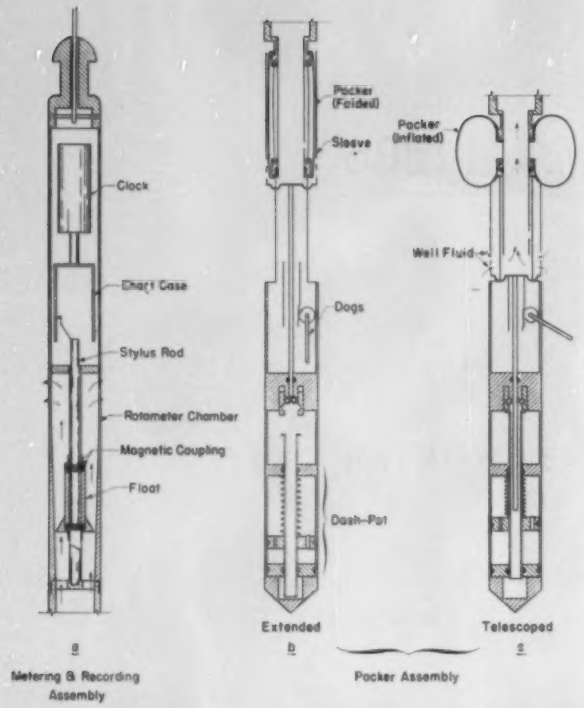


FIG. 1 — SCHEMATIC DIAGRAM OF SUBSURFACE FLOWMETER.

its upper end by a fishing neck to which the supporting wire line is attached. The upper portion of the instrument, shown schematically in Fig. 1a, is the metering and recording assembly. Metering of the fluid flowing in the well is accomplished by means of a modified rotameter, or variable-area meter, through which fluid flowing upward raises a bob or float to a height unique for the particular rate of flow. A time record of the height of the float above its initial or rest position is made by a stylus that moves vertically with the float and contacts a rotating chart mounted in the conventional clock and chart mechanism used in Humble bottom-hole pressure and temperature gauges.

The packer assembly, or lower portion of the flowmeter, is shown schematically in Figs. 1b and 1c. This portion of the instrument attaches directly to the lower end of the metering and recording assembly. The packer assembly includes at its upper end a thin rubber packer mounted on a hollow collapsible mandrel. The packer is enclosed in a metal sleeve to protect it from abrasion when the flowmeter is lowered into the well through the tubing. After the flowmeter has reached the lowest depth at which a measurement is desired, and after the elapse of a predetermined interval of time, the sleeve around the packer is retracted automatically and the packer is freed for inflation and setting at the desired depth. The packer may then be filled with well fluid and set by slackening of the wire line. After sufficient time has elapsed for a flow measurement to be made, the packer may be collapsed and unsealed by raising the instrument. Then it can be reset by slackening the wire line at successively higher levels for as many flow measurements as desired. After measurements have been completed, the flowmeter may be brought back into the tubing and to the surface with no difficulty.

DETAILS OF INSTRUMENT

SIZE

The flowmeter is approximately 7½ ft long and, when the packer is enclosed in its protecting sleeve, has a maximum outside diameter of 1⅝ in. The recording and metering assembly accounts for about 2½ ft of the total length, and the packer assembly for the remainder. The weight of the instrument is roughly 40 lbs. Since the instrument is somewhat larger than a conventional subsurface pressure gauge, it requires a slightly larger lubricator than that used in subsurface pressure work.

METERING AND RECORDING ASSEMBLY

A rotameter was selected for the metering element because it can be easily fabricated with the desired sensitivity over a considerable flow range, and above this range can pass fluid at very high rates of flow without metering it. The rotameter consists of an upright conical chamber in which the float, circular at any horizontal cross section and approximating in maximum diameter the neck of the conic chamber, is free to seek its level when fluid is directed upward through the chamber. The float has a hole concentric with its neutral axis so that the float may move freely in the chamber along a vertical guide rod mounted centrally in the chamber. A rotameter is essentially a constant pressure-drop device with the pressure drop dependent on the weight, density, and maximum diameter of the float. The sensitivity of the device, that is, the amount that the position of the float varies vertically for a change in flow rate, depends on the taper of the metering chamber. The float is shaped to minimize effects of varying fluid viscosity on the readings, and by using a high-density float the effect of varying fluid density is minimized.

It was decided that for use in a subsurface flowmeter the rotameter should give positive indication of flow at extremely low rates and should meter flow in excess of 100 B/D. To achieve this, the conical shape of the rotameter chamber was altered to incorporate a short cylindrical section below the conic section, so that even a small flow would raise the float the full height of the cylindrical section of the chamber.

The clock and chart mechanism used for recording movement of the float must be enclosed in a fluid-tight chamber. In order to record the position of the float during a flow measurement without resorting to some type of packing gland around the linkage connecting the float to the chart stylus, use was made of magnetic coupling.

In order to do this, the float is made in modified cylindrical form to incorporate a hollow cylindrical magnet. It is mounted to slide on a hollow non-magnetic stainless steel guide tube fixed along the neutral axis of the rotameter chamber. A small solid cylindrical follower magnet, similar in length to the float magnet, was installed inside of the guide tube. This follower magnet, to which is attached a thin, light, aluminum tube terminated by a stylus, aligns itself to the height of the outside magnet when the two magnets are polarized oppositely. The bottom end of the guide tube is sealed against the well pressure, and the upper end, through which the stylus rod projects, opens into the

clock case. The stylus rod projects up inside the rotating chart case and records on the chart the height of the metering element as a function of time. The stylus rod is prevented from rotating with the chart by three projecting arms, each with bearings which are free to move only longitudinally in a slotted stationary member which also projects up into the chart case. The stylus projects through a fourth slot in this slotted member.

With this arrangement, flow rates of as low as 4 bbl of liquid per day are perceptible, and a rate of 125 B/D gives a stylus movement of 5 in. Flow rates between 4 and 125 B/D give displacements of the float which are almost linear with flow rates. In this range of flow the pressure drop across the metering element is equivalent to about 5 in of water head. This pressure drop increases as the rate of flow exceeds about 125 B/D.

Packer Assembly

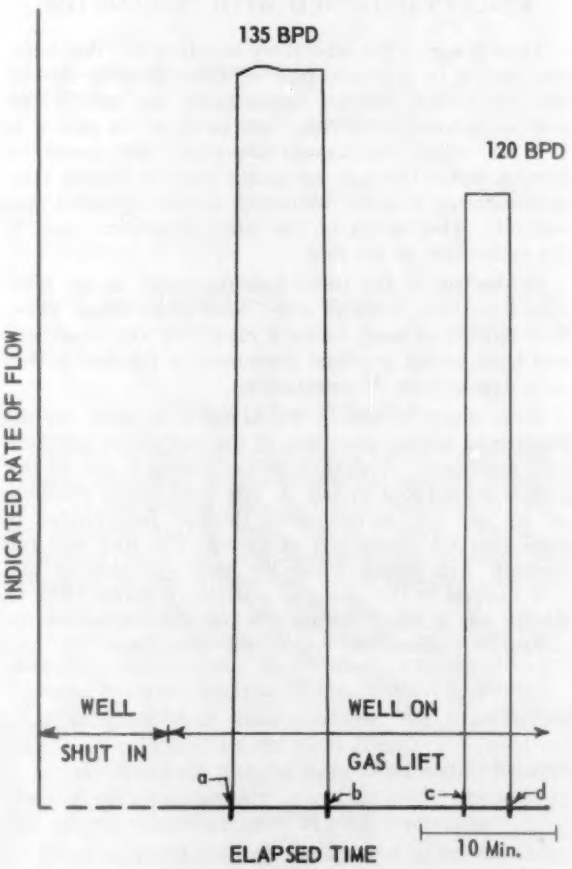
The packer used to divert all flow through the rotameter chamber consists of a preformed football-shaped bladder made of thin oil-resistant rubber. Packers of different diameters are used for different pipe sizes. The packer is attached by ring-shaped clamps at its ends. One clamp is fixed to the end of a hollow mandrel projecting through the bladder along its neutral axis. The other clamp slides along the mandrel. Inside the bladder, six thin stainless steel springs about 14 in long connect the two clamps, with their ends hinged to the clamps. These are mounted equally spaced about the packer mandrel. Ports in the mandrel are so arranged that when the packer clamps are telescoped slowly the springs first bow outward and draw well fluid through the ports to fill but not stretch the packer. Further telescoping covers the mandrel ports and subjects the entrapped fluid to compression, which causes the packer to assume a toroidal shape when not confined by a wellbore. In a borehole the packer thus forms an effective low-pressure seal between instrument and wellbore. On the flowmeter this rubber form is folded about the mandrel and is protected by a hollow enveloping cylindrical metal sleeve when the instrument is lowered into the well.

A spring-loaded dashpot filled with a viscous silicone fluid serves as a timer which, after a preselected time interval, triggers a release. This release allows the well pressure to force the protecting sleeve down off the packer, which action in turn causes a set of three dependently acting dogs to project out from the instrument. These dogs are mounted below the packer mandrel and, when released, prevent further lowering of the bottom section of the instrument in the wellbore. After the dogs have been released and contact the wellbore, any slackening of the wire line supporting the instrument causes the packer section to telescope, thus effecting a seal between instrument and wellbore. Fluid flowing in the wellbore is diverted through ports into the rotameter chamber for measurement.

If the flow rate in the well is greater than about 160 B/D, the pressure drop across the rotameter equals the pressure drop which the packer will withstand, and fluid by-passes the packer. This feature was incorporated intentionally so that high flow rates would not blow the instrument up the hole. Should measurements of rates greater than about 125 B/D be required, the rotameter may be modified to accommodate them with no alteration of the packer.

Injection Flowmeter

In order to adapt the flowmeter for measurement of downward flow in wellbores, a special metering section was made which is interchangeable with the metering assembly described above. In a conventional rotameter the force tending to restore the metering float to its initial or lower-most position is the force of gravity. In a rotameter suitable for measurement of downward flow an inverted conical chamber must be used, and some constant force acting upward must be applied to the float. In the metering assembly designed for downward flow, this constant restoring force is obtained from the buoyant force imparted to a plastic cylinder totally immersed in mercury. This force is transmitted by a thin rod linkage joining the plastic cylinder to the float. The deviation from constancy of this force with position of the totally immersed plastic cylinder is equal to the variation of the buoyant force acting on the thin rod, and, percentagewise, this is a small portion of the total buoyant force.



a Packer set
b Packer unseated
c Packer set at higher level
d Packer unseated

Fig. 2 — Chart-Flowmeter Survey of Oil Well on Gas Lift.

OPERATING PROCEDURE

In the field operation of the instrument, a chart is inserted in the clock case and the clock is wound and returned to its case. In inserting the clock an identifiable mark of some sort is made at the initial position of the stylus, and the exact time is recorded. Then the dashpot is cocked by removing the instrument nose and retracting the dashpot piston to its extreme position. After the time has been recorded, the instrument nose is replaced, and the instrument is lowered in the well in the manner used in lowering bottom-hole pressure instruments. When the instrument has reached a depth equal to or greater than the lowest survey point desired, the reel brake is set and the instrument is kept at this level until the required time interval has elapsed for the dashpot to trigger the packer sleeve release. Flow rate readings are then taken at the desired depths by first raising the instrument in turn to each desired depth and then slackening the line. A line tension indicator is used to ascertain correct functioning of the dogs. The record, then, is like a vertical bar graph, with the widths of the bars indicating reading time durations, and the heights of the bars indicating flow rates.

RESULTS OBTAINED WITH FLOWMETER

Tests made in the laboratory in which the flowmeter was placed in a plastic pipe of 8-in diameter showed that the packer inflated satisfactorily and would support a pressure differential across it of as much as 2 ft of water. Additional laboratory tests made by flowing water through the plastic pipe at known rates demonstrated that the rotameter section operated successfully. The results of the latter tests were used in the calibration of the tool.

In the use of the subsurface flowmeter in the field, runs have been made in seven wells in six fields. These runs have been made under a variety of well conditions and have served to reveal limitations of the tool as well as to demonstrate its potentialities.

Runs made in one of the seven wells were for the purpose of testing operation of the tool under optimum well conditions. A chart obtained during a run in this well is reproduced in Fig. 2. The well, which produces oil by gas lift, is completed through perforations in stub liner set inside 5½-in casing. The tool was run through 2-in tubing while the well was shut in and was stopped in the casing at a depth of about 5,950 ft, which was a short distance below the bottom of the tubing and above the top of the stub liner. The well was then placed on production by gas lift at a rate of approximately 130 BOPD, and the packer was set. After sufficient time for a flow reading had elapsed, the packer was unseated by raising the tool several feet. Then it was reset at the higher level.

The flow rates indicated by the chart were about 135 B/D at the first setting, and about 120 B/D at the second setting. The time intervening between the two settings was about 10 minutes. It is not certain whether the difference in the two indicated rates was real and due to heading of the produced fluid, or whether the difference was due to instrumental causes.

The runs made in the other six of the seven wells were for the purpose of diagnosing well performance, rather than for checking operation of the flowmeter itself. The six wells included one water injection well, which provided an opportunity for use of the modification of the flowmeter designed for measurement of downward flow. In four of the six wells the results were satisfactory from the standpoint of yielding the information sought on well behavior. In the other two, loose sand was encountered which fouled the tool so badly that it would not operate. Since it is anticipated that loose sand will be found in many wells in which subsurface flow measurements are desired, measures are being taken to minimize difficulties from this source.

SUMMARY

In summary, the subsurface flowmeter embodying a rotameter flow measuring element and an inflatable packer which diverts all flow through the rotameter has proved to be reasonably successful in the field. It has been run experimentally in seven wells and has yielded information valuable from the operating standpoint in five of the seven wells, encountering difficulties because of loose sand in the other two wells.

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PETROLEUM TRANSACTIONS

DIMENSIONALLY SCALED EXPERIMENTS and the THEORIES on the WATER-DRIVE PROCESS

G. A. CROES
N. SCHWARZ

KONINKLIJKE/SHELL-LABORATORIUM
AMSTERDAM

T.P. 4009

ABSTRACT

This paper reports the results of a series of model displacement experiments carried out for measuring the efficiency of the water-drive process. This series forms a continuation and extension of that described by Engelberts and Klinkenberg. Detailed information has been obtained on the influence of the oil/water viscosity ratio. The results are represented in the form of a diagram from which both the oil recovery and the water/oil ratio can be easily read off as a function of the total production (oil plus water) for all values of the viscosity ratio M between 1 and 500.

These results are viewed in the light of the two existing theories on water flooding, viz. that of Buckley and Leverett and that of Dietz.

It is shown that if the Buckley-Leverett theory applies, the relation between the relative permeability ratio and saturation, which plays a major role in this theory, can be calculated with a high degree of accuracy from the results of the model experiments.

Dietz's theory is found to be in agreement with the experimental results in a certain range of circumstances. A discussion of the physical background of the Buckley-Leverett and Dietz theories makes it clear why the latter fails to agree with some of the experimental results.

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Discussion of this and all following technical papers is invited. Discussion in writing (3 copies) may be sent to the offices of the Journal of Petroleum Technology. Any discussion offered after Dec. 31, 1955, should be in the form of a new paper.

INTRODUCTION

For an economical exploitation of oil fields both a rational control of natural (primary) recovery processes and a proper application of artificial (secondary) recovery methods are essential. These require detailed information upon the dependence of the relevant flow processes on the variables by which they are governed.

Three methods are available for obtaining this information: (1) (statistical) analysis of actual field data; (2) appropriately scaled model experiments; and (3) mathematical analysis of the physical problem.

If sufficient data were available, the first method would, in principle, be the most reliable one, although it has the drawback that the basic relationships between the variables involved are to a large extent obscured by the natural inhomogeneities of most reservoirs.

The most profitable procedure seems to be: (a) determining the fundamental relations for idealized reservoirs by methods (2) and (3); (b) checking the consistency of the results obtained by these two methods; and (c) establishing the range of applicability of these methods to actual reservoirs by comparison with the data accumulated under (1).

In this paper items (a) and (b) are dealt with for the case of homogeneous loose sands initially saturated

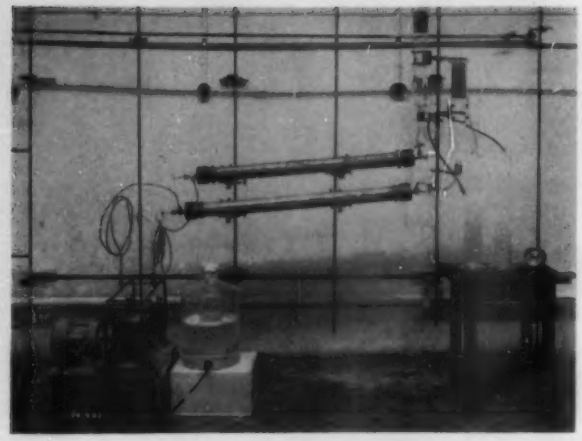

FIG. 1 — APPARATUS FOR MODEL DISPLACEMENT EXPERIMENTS.

with oil that is subsequently displaced by linear complete water drive.

Pertinent model experiments have been carried out by Leverett et al.[1], and by Engelberts and Klinkenberg[2]. Their (mainly qualitative) results have confirmed that the oil/water viscosity ratio M is one of the major factors governing the efficiency of the displacement process, particularly at high values of M. The provision of detailed and quantitative data with respect to the influence of this ratio on reservoir performance is the first purpose of this paper.

Two theories on the displacement of oil by water have been proposed, by Buckley and Leverett[3] and by Dietz[4], respectively. The second purpose of this paper is to check the concurrence of the above experimental results with theoretical predictions.

MODEL EXPERIMENTS

The variables governing flow of mass or energy can be combined to a limited number of mutually independent dimensionless groups which suffice to define the process. For the study of such flow phenomena as occur in nature or industry, they are often simulated in the laboratory on a reduced scale. If the geometry in such experiments is made similar to that in the prototype, and if in both cases the dimensionless groups are given the same values, the experiments are dimensionally scaled and are called model experiments.

Model experiments are extensively used to study problems of hydro- and aerodynamics and of heat transfer. Their use in oil production research has hitherto been rather restricted, although they offer the great advantage of eliminating end effects that make the interpretation of non-scaled experiments difficult.

The model used in the experiments described in this paper is a tube of 1 m length and 6.2 cm diameter, filled with sand. The sand is saturated with oil which is subsequently displaced by water. The outflowing oil and water are measured as a function of the input. The model may be compared to a section of an unconsolidated oil sand that is linearly flooded by water.

The experiments are an extension of those done by Engelberts and Klinkenberg[2], use being made of the same dimensionless groups, viz.:

$$\frac{l}{h};\ a;\ \frac{\eta_o}{\eta_w};\ \frac{\Delta\rho g k}{v\,\eta_w};\ \frac{\Delta\rho\, g h\sqrt{k}}{\gamma\cos\Theta}.$$

The experiments were carried out in the apparatus shown in Fig. 1, which is essentially the same as that used by Engelberts and Klinkenberg.

From a storage tank distilled water is pumped by a plunger pump at a constant rate of 2.05×10^{-4} m/sec into the stainless steel model tube containing the oil-saturated sand. The oil produced is measured in an inverted graduated cylinder filled with water, and, as a check on the constancy of the pump, the total production is measured in an open graduated cylinder. The apparatus is placed in a thermostat room at 25°C. Fig. 1 shows a double set-up in which two experiments are run simultaneously.

After each experiment the sand in the tube is cleaned by washing it with chloroform and acetone and dried by blowing air through it. The sand is then ready to be resaturated with oil. This is done by means of another pump, the tube being kept in a vertical position. The oil is fed in at a very low rate and, in the case of low viscosity oils, under reduced pressure, so as to avoid the inclusion of air bubbles in the sand.

Use was made of a 20-30 mesh sand having a permeability of 2×10^3 md and a porosity of 33 per cent and of an SAE 30 lubricating oil. The viscosity ratio was varied by mixing the oil with kerosene.

As stated in the introduction, the objective of the present experiments was to evaluate quantitatively the

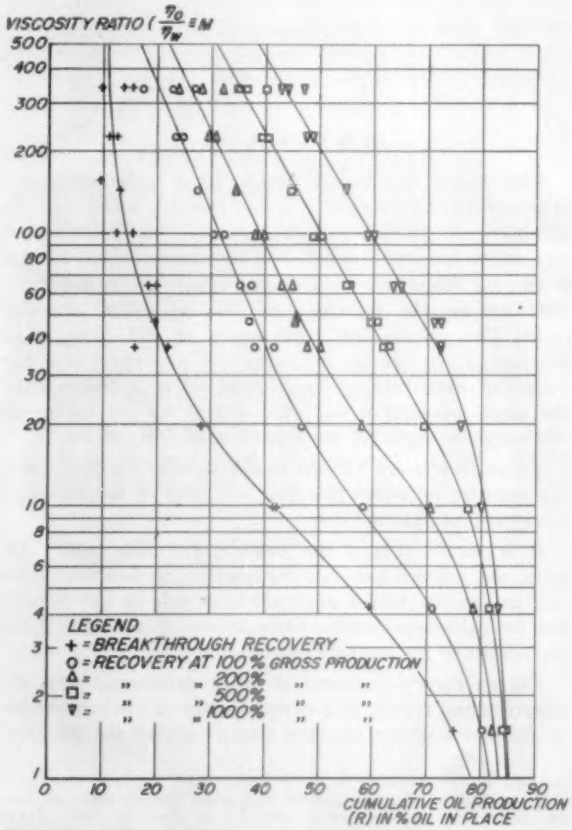

FIG. 2 — VISCOSITY RATIOS VS CUMULATIVE OIL PRODUCTION FOR VARIOUS VALUES OF GROSS PRODUCTION.

[1]References given at end of paper.

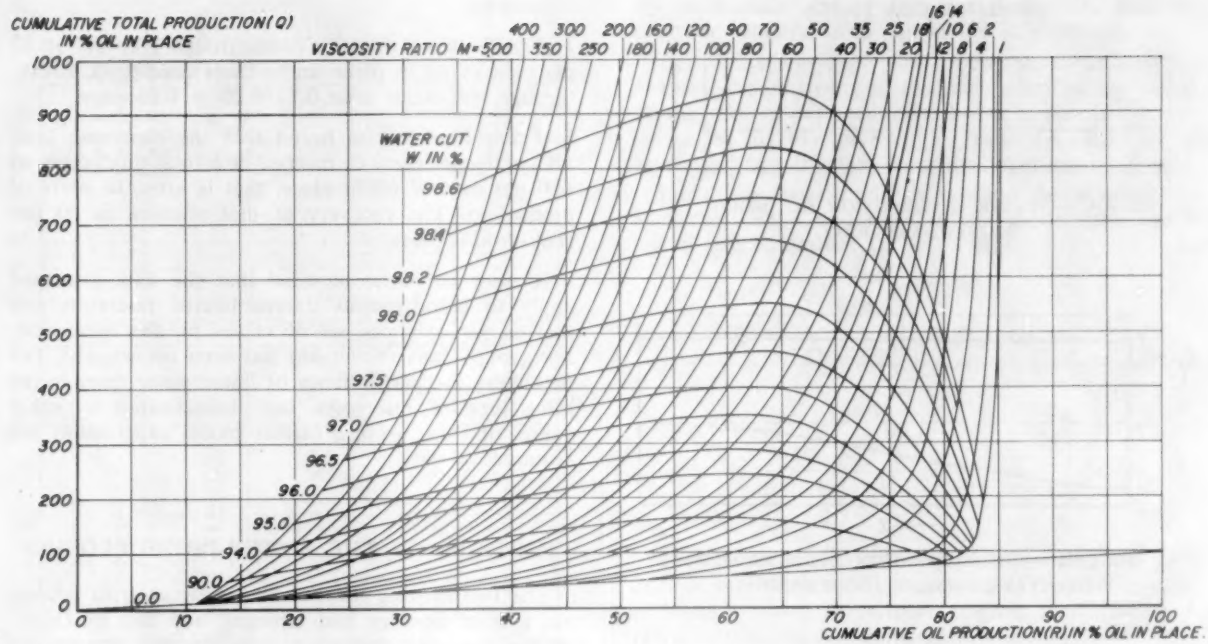

FIG. 3 — CUMULATIVE TOTAL PRODUCTION VS CUMULATIVE OIL PRODUCTION ACCORDING TO MODEL EXPERIMENTS.

influence of the oil/water viscosity ratio on the displacement process. For this reason the group η_o/η_w was varied from 1 to 500, while the other groups were given constant values listed in Table 1.

TABLE 1 — VALUES OF DIMENSIONLESS GROUPS

$\frac{l}{h}$	= 16.1
α	= arctan 1/12 = 4°45'
$\frac{\Delta\rho g k}{v\,\eta_w}$	= 1.3
$\frac{\Delta\rho g h\sqrt{k}}{\gamma\cos\Theta}$	= 0.04

EXPERIMENTAL RESULTS

The experimental results obtained for a given oil/water viscosity ratio M can be most conveniently represented by a plot of the cumulative total (gross) production Q vs the cumulative oil production R (recovery), both expressed as a percentage of the initial oil in place. If M is given several values, a set of curves results, viz. one for each value of M. In each point of the curves the instantaneous water content W of the fluid produced (water cut) can be derived by means of the relation

$$W = 1 - \frac{dR}{dQ} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Now another set of curves Q vs R can be constructed for various constant values of W.

However, it was found that even after eliminating all possible sources of experimental errors, the data accumulated still show appreciable scattering, particularly the derived W values. A suitable method of averaging these data had, therefore, to be developed. This problem could be solved with the help of Fig. 2, which gives the values of the recovery R at breakthrough and at gross productions Q of 100, 200, 500, and 1,000 per cent of oil in place as a function of the logarithm of the viscosity ratio M.

This graph shows that:

1. In the region $500 > M > 40$ the curves Q = constant are approximately straight lines.
2. In the region $1 < M < 40$ the curves Q = constant approach a limit of $R \approx 85$ per cent for $M = 1$.

The "best fitting" curves were drawn through the experimental points. From these (averaged) curves the plots Q vs R (for M constant) could easily be drawn (Fig. 3). The water cut W was then determined graphically, using Equation 1, for various values of R. Interconnection of the points representing equal values of W yields the curves Q vs R for W = constant, which are also given in Fig. 3. Since Q vs time is a known function, the functions R and W vs time can also be derived from Fig. 3.

The straight line in Fig. 3 connecting the points (0,0) and (100,100) represents $W = 0$, i.e. the production of dry oil. At the points where the curves depart from this line, water breakthrough occurs for the particular viscosity ratio corresponding to the curve. In these points W appears to rise sharply from 0 to a certain value > 0.

The physical factors determining the shape of the curves Q vs R for M constant, in the range of interest as shown in Fig. 3, are fundamentally different for high and for low viscosity ratios.

For $M >$ about 100 the viscous resistance to flow after breakthrough will be much greater for oil than for water. The water will travel through the sand in channels (fingers), leaving patches of oil untouched. The water cut will show a sharp rise, whereas the cumulative oil production will increase but slowly: we are in the typical viscous fingering region. The lower

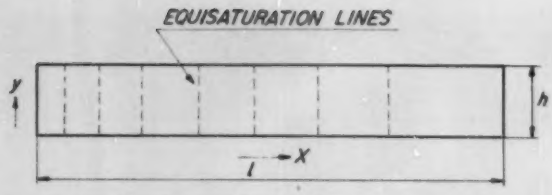

FIG. 4A — WATER DISTRIBUTION ACCORDING TO BUCKLEY-LEVERETT.

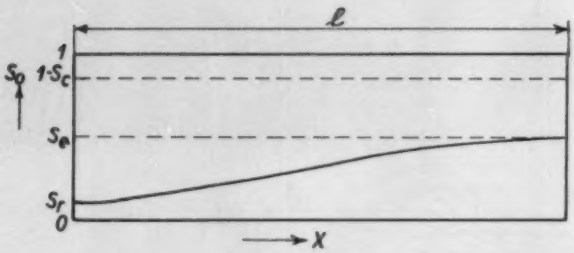

FIG. 4B — OIL SATURATION ACCORDING TO BUCKLEY-LEVERETT (SCHEMATIC).

the value of M, the less pronounced these phenomena, and in the region of $100 > M > 40$ the water cut increases more slowly. For still lower values of M the amount of oil retained by capillary forces (the residual oil, about 15 per cent of oil in place) is the controlling factor of the displacement after breakthrough. The cumulative oil production approaches this limit of the ultimate recovery very soon after water breakthrough, and the rate of oil production declines rapidly, as is illustrated by a steep bend upwards of the curves and a sharp increase of the water cut.

The above is further borne out by the Q vs R curves for W constant. These curves appear to converge to one point on the right-hand side of the figure. This can easily be explained from the behavior of an extremely fluid crude. In this case no fingering will occur. The M = constant line will coincide with the straight line through the points 0,0 and 100,100, the 0 per cent water line, until a production of 85 per cent is reached. From that moment onwards only water will be produced (W = 100 per cent) so that the vertical straight line $R \approx 85$ will be followed. Thus all curves W = constant should converge to a point in the neighborhood of (85,85). From Fig. 3 it can be seen that $M = 1$ is a good approximation for a low-viscous oil.

The principle of the application of these diagrams for the prediction of reservoir performance can best be illustrated by an example.

Given: a linear water-drive reservoir with characteristics such that the dimensionless numbers are in the same range as those of the present experiments; viscosity ratio, 60; gross production rate, 20 per cent of the oil in place per year.

Questions:

1. What is the breakthrough recovery and after what time does breakthrough of water occur?

2. When will the economic limit (e.g. 98 per cent water in the production) be reached, and how much oil has been recovered at that moment?

Answers:

1. Fig. 2 shows that the breakthrough recovery is 17 per cent of oil in place under these conditions. Breakthrough will occur after 0.17/0.20 = 0.85 years.

2. From Fig. 3 it is found that the economic limit (W = 98 per cent) is reached at a total production of 670 per cent of oil in place, that is after 34 years of production. The recovery at that moment is 60 per cent of oil in place.

It must be borne in mind that the data presented apply to homogeneous unconsolidated reservoirs and that as yet only one set of values for the dimensionless groups (apart from M) has been investigated. For predicting the performance of linear water drive in the same type of reservoirs, but characterized by other values of these groups, further model experiments are required.

THEORIES ON THE WATER-DRIVE PROCESS

The two existing theories on the water-drive process are that of Buckley and Leverett[3] and that of Dietz[4]. In the following discussions it is assumed that gravity and capillary forces may be neglected with respect to the viscous forces. The displacement process is considered to take place in a rectangular formation of length l, height h and unit width. The co-ordinate in the direction of flow is x, that perpendicular to it is y. Thus $0 \leq x \leq l$, and $0 \leq y \leq h$. The initial oil/water interface ($x = 0$) is assumed to be perpendicular to the direction of flow. With these assumptions the two theories can be characterized as follows.

According to the Buckley-Leverett theory the invading water progresses with the formation of a front, cf. Fig. 4A. The water is evenly distributed over the entire reservoir height, i.e. the equi-saturation lines (dotted in the figure) are parallel to the original oil/water interface.

Oil and water flow simultaneously through a porous medium with a relative permeability K_o to oil and a relative permeability K_w to water. K_o and K_w are functions of the oil saturations s_o and thus of the water saturation $s_w = 1 - s_o$.

Application of the Buckley-Leverett theory is hampered by the difficulty of measuring the relative permeability vs saturation curves that form the starting point of the calculations according to this theory.

In the Dietz theory it is assumed that the water invades the oil reservoir in the form of a water tongue along the bottom (Fig. 5).

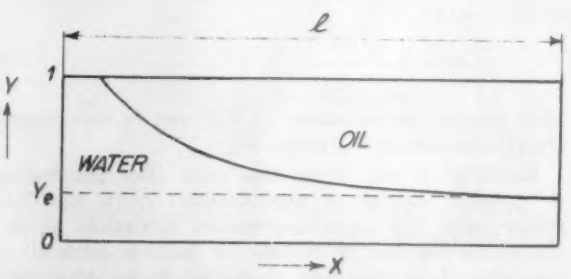

FIG. 5—WATER SATURATION AND SHAPE OF THE WATER TONGUE ACCORDING TO DIETZ (SCHEMATIC).

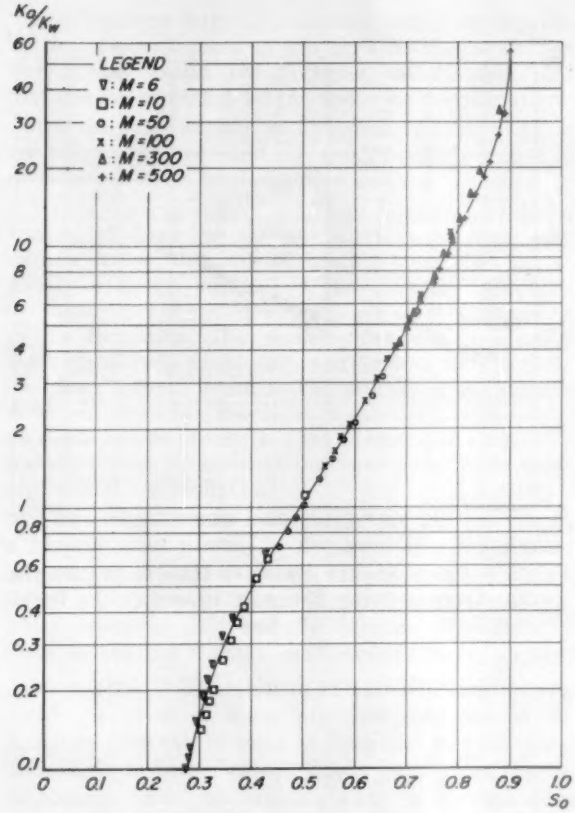

FIG. 6 — RELATIVE PERMEABILITY RATIO VS OIL SATURATION ACCORDING TO BUCKLEY-LEVERETT'S THEORY.

The oil saturation in the invaded region is instantly reduced to the residual oil saturation s_r, so that there is always a definite interface between the invaded and uninvaded zones. Oil and water flow separately: the oil, ahead of the interface, through a porous medium with an irreducible (fixed) water saturation s_c and therefore a constant relative permeability K_o' to oil, the water in the water-invaded part through the water tongue with height $hY(x)$, a fixed oil saturation s_r and thus a constant relative permeability K_w' to water.

Application of the Dietz theory is considerably simpler than that of the Buckley-Leverett theory because only two points of the (questionable) relative permeability curves have to be known. It should be remarked that the Dietz theory is not affected by assuming the presence of more than one water tongue, if only the total height of the water tongues is at any moment equal to that of the corresponding single tongue in any cross section perpendicular to the direction of flow. If there are a great many water tongues, the difference between both theories fades away as regards the distribution of oil and water.

CALCULATION, FROM THE EXPERIMENTS, OF THE RELATIVE PERMEABILITY RATIOS USING BUCKLEY-LEVERETT'S THEORY

The most straightforward check of the theories would be to calculate directly from them the relation between cumulative total production (Q) and cumulative oil production (R), both expressed as a fraction of the oil in place for different values of the oil/water viscosity ratio (M), and to compare the results with the diagram obtained from the model experiments.

It is difficult to apply this procedure to the Buckley-Leverett theory owing to the uncertainty of the values of the relative permeabilities. But it is possible to calculate the relative permeability ratio (K_o/K_w) vs oil saturation (s_o) function from the experimental data.

For this purpose a relation between the oil saturation s_e at the outflow end $x = l$ of the model tube and R and Q can be derived (cf. Fig. 4B):

$$R = \frac{1}{l\,(1 - s_c)} \int_{s_r}^{1-s_c} x\, ds_o, \quad \text{or}$$

$$R = \frac{1 - s_e - s_r}{1 - s_c} + \frac{1}{l\,(1 - s_c)} \int_{s_r}^{s_e} x\, ds_o. \quad (2)$$

The basic equation, relating position along the path of flow, saturation and time in terms of the total amount of water entering the system, is given in Reference 3 (Equation 5). In our nomenclature it may be written:

$$x = -\,(1 - s_c)\, l\, Q\, \frac{dW}{ds_o} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Substitute (3) into (2):

$$R = 1 - \frac{s_e}{1 - s_c} - Q \int_1^{W_e} dW = 1 - \frac{s_e}{1 - s_c}$$

$$- Q\,(W_e - 1) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where W_e is the value of W for $x = l$. If $s_o = s_r$, no oil can further be recovered and thus $W = 1$.

From (4) the equation relating s_e to Q and R results (W is written for W_e; W is related to Q and R by (1):

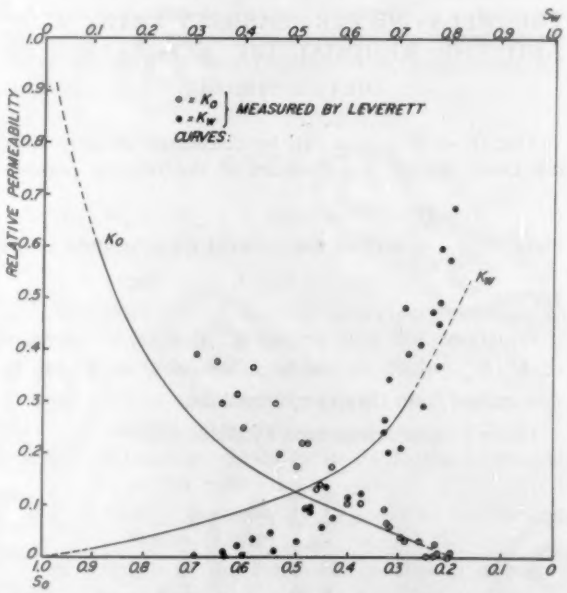

FIG. 7 — COMPARISON OF THE RELATIVE PERMEABILITY CURVES WITH LEVERETT'S DATA.

$$s_e = (1 - s_c)\,[1 - R + Q\,(1 - W)] \quad (5)$$

This equation has been derived previously by Welge[6], Equation 7.

From Darcy's law as used by Buckley and Leverett (neglecting capillary and gravity forces):

$$v_o = \frac{K_o k}{\eta_o}\,\frac{dP}{dx}$$

$$v_w = \frac{K_w k}{\eta_w}\,\frac{dP}{dx}$$

It follows that the water content of the emerging fluid is given by:

$$W = v_w/(v_o + v_w) = 1/(1 + K_o\eta_w/K_w\eta_o) \quad . \quad (6)$$

which is identical with Equation 3 of Reference 3.

With the aid of (5) and (6) the curve K_o/K_w vs s_e can be constructed, for every value of M at which the relationship between Q and R is known, by plotting $M\,(1 - W)/W$ against $(1 - s_c)\,[1 - R + Q\,(1 - W)]$, Fig. 6. In our experiments no connate water was present, i.e. $s_c = 0$.

The graph presents striking evidence for the independence of the relative permeability ratio from the viscosity ratio. Although this fact has been stated earlier by Leverett[3] and others, the spread in the results of their direct measurements does not allow an unambiguous conclusion. The spread in the results presented in Fig. 6 is much smaller, so that the method proposed seems to be a more accurate way of determining K_o/K_w values than direct measurement. However, more experiments with other values of the dimensionless groups are required to confirm the data obtained.

By trial and error, K_o and K_w vs s_e curves have been derived from the curve of Fig. 6, in such a way that the best possible agreement is obtained with Leverett's experimental data. The result is demonstrated in Fig. 7.

CALCULATION, FROM THE EXPERIMENTS, OF THE "RELATIVE PERMEABILITY RATIO" K'_o/K'_w AND THE RESIDUAL OIL SATURATION OF DIETZ'S THEORY

The Q vs R curves can be calculated directly from the Dietz theory if the values of the relative permeability ratio $\frac{K'_o}{K'_w}$ and of the residual oil saturation s_r are known.

Equations will now be derived that allow the value of K'_o/K'_w (which should be independent of Y), to be determined from the experimental data.

Darcy's equations as used by Dietz read

$$v_o = \frac{K'_o k}{\eta_o}\,(1 - Y)\,\frac{dP}{dx}$$

$$v_w = \frac{K'_w k}{\eta_w}\,Y\,\frac{dP}{dx}$$

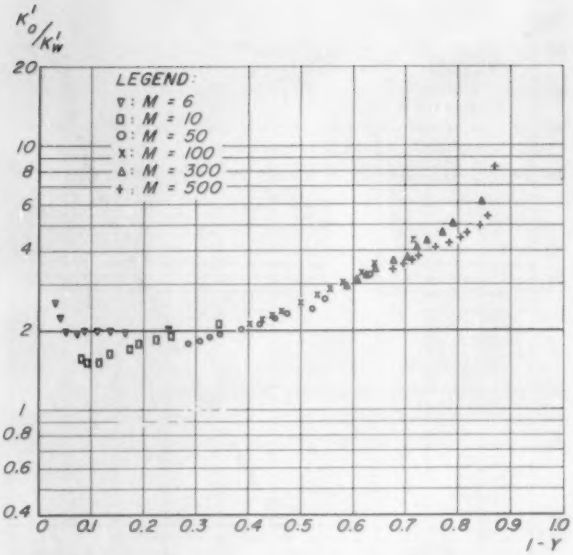

FIG. 8 — PERMEABILITY RATIO VS HEIGHT OF THE OIL LAYER ACCORDING TO DIETZ'S THEORY ($s_r = 0.24$).

From these, Equation 18 of Reference 4 follows:

$$W = \frac{Y}{Y + a\,(1 - Y)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

and

$$\frac{dW}{dY} = \frac{a}{[Y + a\,(1 - Y)]^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where $a = K'_o\,\eta_w/K'_w\,\eta_o$.

The equation for the Dietz theory corresponding to Equation 3 for the Buckley-Leverett theory can be derived by substituting (8) in Equation 25 of Reference 4. It reads:

$$x = \frac{1 - s_c}{s_d}\,Ql\,\frac{dW}{dY} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

From Fig. 5 it can be shown that:

$$R = \frac{Y_e\,s_d}{1 - s_c} + \frac{s_d}{1 - s_c}\int_{Y_e}^{1} \frac{x}{l}\,dY \quad . \quad . \quad (10)$$

Substituting (9) into (10):

$$R = \frac{Y_e\,s_d}{1 - s_c} + Q\int_{W_e}^{1} dW = \frac{Y_e\,s_d}{1 - s_c} + Q\,(1 - W_e) \quad . \quad (11)$$

Dropping the subscript e, (11) can be written as:

$$Y = \frac{1 - s_c}{s_d}\,[R - Q\,(1 - W)] \quad . \quad . \quad . \quad (12)$$

With the aid of (7) and (12) K'_o/K'_w can be found for every value of M at which Q is known as a function of R, if a certain value of s_r is assumed. In Fig. 8 K'_o/K'_w is plotted vs $1 - Y$, for $s_r = 24$ per cent.

It can be seen that only in the left part of the diagram do the points lie more or less on a horizontal straight line, as they should. The discrepancy in the right-hand part can be explained by the following considerations.

The theory of Buckley and Leverett and that of Dietz are believed to represent the two extreme possibilities of the water-drive mechanism.

When water displaces oil from a porous medium, somewhere along the oil-water interface the water may intrude farther into the oil-bearing layer than corresponds with the position of the interface. This can be initiated, for instance, by a slight inhomogeneity of the formation. The resulting pressure distribution will subsequently cause the water to flow preferentially into the "fingers" formed. The process is cumulative. A second important phenomenon associated with water-oil displacement processes is the existence of a capillary transition zone between the oil-bearing and water-bearing parts of the formation.

When displacement experiments are carried out in a narrow tube, narrow in the sense that the dimensionless group $\triangle\rho gh\ \sqrt{k}/\gamma \cos \Theta$ is small, the capillary forces will "smear out" the fingers. In this case the water saturation is essentially constant throughout a cross section and Buckley and Leverett's theory applies.

In a very "wide" tube or in a "thick" oil sand, $\triangle\rho gh\ \sqrt{k}/\gamma \cos \Theta$ being large, the thickness of the transition zone will be small as compared with the other dimensions involved. Dietz's theory of a water tongue by-passing the oil corresponds with the extreme case of a negligible value of this thickness. However, the tip of the tongue will be thin in any case, and there will therefore be a region where it is not permissible to assume that the thickness of the transition zone is small as compared with the thickness of the tongue. For thick sands this region will be comparatively unimportant.

The above suggests that there exists a minimum tongue thickness, below which deviations from Dietz's theory may be expected. According to Fig. 8 this value is $Y_e \cong 0.5$ for our experiments. For wider tubes the region of deviation might be expected to be smaller, but this point remains to be checked by additional experiments.

In the experiments described in this paper the group $\triangle\rho gh\ \sqrt{k}/\gamma \cos \Theta$ had a value of 0.04* as compared to, say, 0.04 − 4 in heavy oil fields. Thus the tubes used may be called "narrow," corresponding to "thin" oil sands.

For such thin sands the Dietz theory has only a limited value; for thicker sands it might have a wider applicability, possibly even for the major part of the flooding process (except the initial stage).

A more complete theory should take into account the Buckley and Leverett process in the transition zone, or in other words, constitute some combination of the two theories with more emphasis on the one or the other, depending on the dimensionless group $\triangle\rho gh\ \sqrt{k}/\gamma \cos \Theta$. Attempts to bring about such a combination have as yet met with little success.

*In conventional, unscaled, displacement experiments the group in question usually has a value of 0.002.

CONCLUSIONS

1. If a given homogeneous unconsolidated oil-saturated sand is flushed with water at a given uniform rate and the cumulative oil production R at given values of the cumulative gross production Q is plotted against the logarithm of the oil/water viscosity ratio M, then (a) for $500 > M > 40$ the curves Q = constant are straight lines, and (b) for $M < 40$ the curves Q = constant converge to a limiting value of R; this limit marks the maximum ultimate recovery which can be obtained by water drive.

2. A diagram is presented from which the cumulative oil production (recovery, R) and the instantaneous water content W of the production, both as a function of the cumulative total production and therefore of time, can be read off for oil/water viscosity ratios M in the range from 1 to 500. This diagram is intended for application to homogeneous reservoirs that are being produced by linear water drive.

3. The relative permeability ratio as a function of saturation can be calculated with greater precision by means of the Buckley-Leverett theory from the results of dimensionally scaled model experiments than by direct measurement.

4. The relative permeability ratio thus derived from our model experiments conforms to the results of earlier investigators, viz. that it is independent of the viscosity ratio of oil to water.

5. The experimental data are in agreement with the Dietz theory if the thickness of the water tongue at the end point of the tube is greater than half the diameter of the tube. For thicker tubes it is to be expected that the agreement will cover a larger range.

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NOMENCLATURE

$a = K'_o \eta_w / K'_w \eta_o$ = mobility ratio (Dietz);
f = porosity;
g = acceleration due to gravity;
h = thickness of the formation perpendicular to direction of flow;
k = one-phase permeability;
K_o = relative permeability to oil;
K_w = relative permeability to water;
K'_o = relative permeability to oil in the unflooded region (Dietz);
K'_w = relative permeability to water in the flooded region (Dietz);
l = length of the formation parallel to direction of flow;
$M = \eta_o/\eta_w$ = oil/water viscosity ratio;
P = pressure;

$Q = \dfrac{1}{lf\,(1 - s_c)} \int_o^t v\,dt$ = cumulative total production expressed as a fraction of oil initially in place;

$R = \dfrac{1}{lf\,(1 - s_c)} \int_o^t v_o\,dt$ = cumulative oil production expressed as a fraction of oil initially in place;

R_b = breakthrough recovery expressed as a fraction of oil initially in place;

s = saturation;

s_c = connate water saturation;

$s_d = 1 - s_c - s_r$;

s_e = oil saturation at the outflow end of the tube;

s_o = oil saturation;

s_r = residual oil saturation;

s_w = water saturation;

$v = v_o + v_w = lf\,(1 - s_c)\dfrac{dQ}{dt}$ = total flow rate per unit area;

$v_o = lf\,(1 - s_c)\dfrac{dR}{dt}$ = oil flow rate per unit area;

v_w = water flow rate per unit area;

$W = \dfrac{v_w}{v} = \dfrac{d\,(Q\text{-}R)}{dQ}$; at the outflow end of the tube it equals the water cut, i.e. the instantaneous water content of the production;

W_e = W at the outflow end of the tube (the subscript e has been omitted throughout the text; only if confusion had to be avoided was W_e written instead of W);

x = co-ordinate parallel to direction of flow; its physical meaning is restricted to $0 \leq x \leq l$;

y = co-ordinate perpendicular to direction of flow; its physical meaning is restricted to $0 \leq y \leq h$;

$Y = \dfrac{y}{h}$; more specifically the ordinate of the oil/water interface (Dietz) as a fraction of formation thickness; $0 \leq Y \leq 1$.

Y_e = Y at the outflow end of the tube;

α = slope of the formation;

γ = interfacial tension oil/water;

η_o = dynamic viscosity of the oil phase;

η_w = dynamic viscosity of the water phase;

$\Delta\rho$ = difference in density between oil and water phases;

Θ = contact angle of the oil/water interface with the sand grains.

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★★★

DIRECT CALCULATION of BOTTOM-HOLE PRESSURES in NATURAL GAS WELLS

YUSUF K. SUKKAR
DAVID CORNELL
JUNIOR MEMBER AIME

UNIVERSITY OF TEXAS
AUSTIN, TEX.

T.P. 4010

ABSTRACT

The fundamental differential equation for fluid flow has been rearranged, integrated numerically for natural gases, and the results presented in tabular and graphical form suitable for the direct calculation of vertical gas flow problems. The integration is rigorous except for the use of a constant average temperature. Both static and flowing bottom-hole pressures may be calculated by this method without resort to trial and error procedures.

INTRODUCTION

Bottom-hole pressures can be determined either by direct measurement with a bottom-hole pressure gauge or by calculation. Since measurement with a bottom-hole pressure gauge is costly, calculation of bottom-hole pressures is to be preferred when possible. Calculation involves knowledge of the wellhead pressure, the properties of the gas, the depth of the well, the flow rate, the temperature of the gas, and the size of the flow line. These quantities must be combined in a suitable equation for vertical flow. Several equations have been developed for the purpose of calculating gas flow through both horizontal and vertical pipes[1,2,4,5,6,7,8,9]. These equations all have the basic differential equation for flow as their starting point. They differ only in the assumptions which are made in order to simplify the integration step. The bottom-hole pressures calculated using any of the better known equations are in good agreement with bottom-hole pressures calculated by a more rigorous but considerably more tedious stepwise integration method. All of these methods, however, require a trial and error solution for the calculation of flowing bottom-hole pressures. The purpose of this paper is to present a method which provides a direct solution of static and flowing bottom-hole pressures without use of a trial and error solution. At the same time the method involves fewer simplifying assumptions than any of the previous methods used, except for the lengthy stepwise method.

[1]References given at end of paper.

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THEORY

The derivation of any practical flow equation begins with the basic differential equation which is rigorous for almost all flow problems.

$$(\bar{V})\ (dP) + \frac{(g)\ (dL)}{(g_c)} + \frac{(v)\ (dv)}{(g_c)} = -d\bar{w}_s - d(\bar{lw}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

The five terms in Equation 1 represent the pressure-volume potential energy, the potential energy of position, the kinetic energy, the shaft work done, and the energy losses due to motion of the fluid respectively. Equation 1 reduces to Bernoulli's theorem for the case of horizontal flow of an incompressible fluid, no work done, and no energy losses due to friction.

In the present case, the term $(v)\ (dv)/(g_c)$ can be shown to be quite negligible compared to the other terms, and is therefore neglected in the derivation. The term $-d\bar{w}_s$ includes work done by a pump or turbine in the system and is zero in this case. The frictional losses in the pipe are included in the term $-d(\bar{lw})$ which is expressed in terms of the Moody friction factor as in Equation 2.

$$d(\bar{lw}) = \frac{(f)\ (v^2)\ (dL)}{(2)\ (g_c)\ (D)} \quad \ldots\ldots\ (2)$$

The specific volume of a gas can be expressed in terms of the temperature, pressure, molecular weight, and compressibility factor.

$$\bar{V} = \frac{(z)\ (R)\ (T)}{(M)\ (P)} \quad \ldots\ldots\ (3)$$

The velocity of the gas can be expressed in terms of the weight rate of flow, the specific volume, and the dimensions of the pipe.

$$v = \frac{(4)\ (W)\ (\bar{V})}{(\pi)\ (D^2)} = \frac{(4)\ (W)\ (z)\ (R)\ (T)}{(\pi)\ (D^2)\ (M)\ (P)} \quad \ldots\ (4)$$

The reduced pressure P_r is to be used because z can be expressed as a function of P_r and T_r alone for most natural gases[3].

$$P_r = \frac{P}{P_c} \quad \ldots\ldots\ (5)$$

TABLE 1

Table of $0.5 + \int_3^{P_r} \frac{(z/P_r)\, dP_r}{1 + B(z/P_r)^2}$

	$T_r = 1.5$				$T_r = 1.6$				$T_r = 1.7$			
P_r	B=0	B=5	B=10	B=20	B=0	B=5	B=10	B=20	B=0	B=5	B=10	B=20
1.0	1.4236	0.9215	0.7876	0.6790	1.4613	0.9233	0.7852	0.6755	1.4927	0.9242	0.7828	0.6719
1.1	1.3380	0.9032	0.7773	0.6735	1.3733	0.9052	0.7751	0.6702	1.4031	0.9063	0.7728	0.6666
1.2	1.2606	0.8838	0.7662	0.6675	1.2939	0.8861	0.7642	0.6643	1.3219	0.8874	0.7621	0.6609
1.3	1.1902	0.8636	0.7545	0.6611	1.2213	0.8661	0.7527	0.6580	1.2476	0.8676	0.7507	0.6547
1.4	1.1255	0.8427	0.7420	0.6562	1.1547	0.8454	0.7404	0.6513	1.1792	0.8471	0.7387	0.6481
1.5	1.0659	0.8212	0.7289	0.6468	1.0931	0.8242	0.7276	0.6440	1.1159	0.8261	0.7260	0.6410
1.6	1.0107	0.7993	0.7153	0.6390	1.0359	0.8025	0.7142	0.6364	1.0570	0.8045	0.7129	0.6336
1.7	0.9603	0.7772	0.7012	0.6308	0.9825	0.7705	0.7003	0.6284	1.0020	0.7827	0.6992	0.6258
1.8	0.9113	0.7549	0.6866	0.6223	0.9325	0.7583	0.6860	0.6201	0.9503	0.7605	0.6851	0.6177
1.9	0.8662	0.7326	0.6718	0.6134	0.8856	0.7360	0.6714	0.6113	0.9018	0.7383	0.6707	0.6092
2.0	0.8238	0.7102	0.6566	0.6042	0.8413	0.7136	0.6564	0.6023	0.8559	0.7159	0.6559	0.6004
2.1	0.7838	0.6880	0.6413	0.5946	0.7994	0.6913	0.6412	0.5930	0.8124	0.6936	0.6408	0.5914
2.2	0.7459	0.6660	0.6257	0.5849	0.7597	0.6691	0.6258	0.5834	0.7711	0.6713	0.6256	0.5821
2.3	0.7099	0.6442	0.6100	0.5748	0.7220	0.6471	0.6102	0.5736	0.7318	0.6491	0.6101	0.5725
2.4	0.6758	0.6226	0.5943	0.5646	0.6860	0.6252	0.5946	0.5636	0.6944	0.6271	0.5946	0.5627
2.5	0.6432	0.6013	0.5785	0.5542	0.6516	0.6036	0.5788	0.5534	0.6585	0.6053	0.5789	0.5526
2.6	0.6121	0.6804	0.5627	0.5435	0.6188	0.5823	0.5630	0.5430	0.6242	0.5837	0.5631	0.5424
2.7	0.5823	0.5597	0.5469	0.5328	0.5873	0.5612	0.5472	0.5324	0.5913	0.5623	0.5473	0.5320
2.8	0.5537	0.5395	0.5312	0.5220	0.5570	0.5405	0.5314	0.5217	0.5597	0.5413	0.5315	0.5214
2.9	0.5263	0.5195	0.5155	0.5110	0.5280	0.5201	0.5156	0.5109	0.5293	0.5205	0.5157	0.5108
3.0	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
3.1	0.4145	0.4807	0.4845	0.4890	0.4729	0.4802	0.4843	0.4890	0.4717	0.4797	0.4842	0.4891
3.2	0.4500	0.4619	0.4692	0.4780	0.4469	0.4607	0.4688	0.4780	0.4443	0.4598	0.4686	0.4781
3.3	0.4262	0.4433	0.4540	0.4666	0.4217	0.4416	0.4534	0.4669	0.4179	0.4402	0.4530	0.4671
3.4	0.4031	0.4251	0.4390	0.4555	0.3973	0.4228	0.4381	0.4557	0.3922	0.4210	0.4376	0.4561
3.5	0.3808	0.4074	0.4241	0.4443	0.3736	0.4043	0.4229	0.4446	0.3674	0.4020	0.4222	0.4450
3.6	0.3590	0.3897	0.4093	0.4331	0.3506	0.3861	0.4079	0.4334	0.3432	0.3833	0.4070	0.4338
3.7	0.3379	0.3724	0.3947	0.4219	0.3283	0.3682	0.3930	0.4222	0.3198	0.3649	0.3918	0.4227
3.8	0.3173	0.3554	0.3802	0.4108	0.3065	0.3506	0.3782	0.4110	0.2970	0.3468	0.3768	0.4115
3.9	0.2972	0.3387	0.3659	0.3997	0.2853	0.3333	0.3636	0.3999	0.2747	0.3289	0.3619	0.4003
4.0	0.2776	0.3222	0.3517	0.3886	0.2646	0.3163	0.3491	0.3887	0.2531	0.3114	0.3472	0.3891
4.1	0.2584	0.3060	0.3377	0.3776	0.2444	0.2995	0.3348	0.3776	0.2319	0.2941	0.3326	0.3780
4.2	0.2396	0.2900	0.3238	0.3665	0.2246	0.2830	0.3206	0.3665	0.2112	0.2771	0.3181	0.3668
4.3	0.2211	0.2743	0.3101	0.3556	0.2053	0.2667	0.3065	0.3554	0.1910	0.2603	0.3037	0.3557
4.4	0.2031	0.2588	0.2965	0.3446	0.1864	0.2506	0.2925	0.3444	0.1711	0.2437	0.2895	0.3446
4.5	0.1853	0.2434	0.2830	0.3337	0.1678	0.2348	0.2787	0.3334	0.1517	0.2274	0.2754	0.3335
4.6	0.1679	0.2283	0.2696	0.3229	0.1495	0.2191	0.2650	0.3224	0.1327	0.2112	0.2614	0.3225
4.7	0.1508	0.2134	0.2564	0.3121	0.1316	0.2037	0.2515	0.3115	0.1140	0.1954	0.2476	0.3115
4.8	0.1340	0.1986	0.2432	0.3014	0.1140	0.1884	0.2380	0.3006	0.0957	0.1797	0.2339	0.3005
4.9	0.1174	0.1841	0.2302	0.2907	0.0966	0.1734	0.2247	0.2898	0.0777	0.1642	0.2203	0.2896
5.0	0.1011	0.1697	0.2173	0.2800	0.0796	0.1585	0.2115	0.2791	0.0600	0.1488	0.2068	0.2787

Combining Equations 1 through 5, the differential equations from which the variables v and $\overline{V}$ have been eliminated is obtained.

$$\frac{(g_c)\ (R)\ (T)\ (z)\ (dP_r)}{(g)\ (M)\ (P_r)} + \left[1 + \frac{(8)\ (f)\ (W^2)\ (R^3)\ (T^2)}{(g)\ (\pi^2)\ (D^5)\ (M^2)\ (P_c^2)} \cdot \left(\frac{z}{P_r}\right)^2\right](dL) = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

For convenience let

$$B = \frac{(8)\ (f)\ (W^2)\ (R^3)\ (T^2)}{(g)\ (\pi^2)\ (D^5)\ (M^2)\ (P_c^2)} \quad . \quad . \quad . \quad (7)$$

and express Equation 6 in terms of B.

$$\frac{\dfrac{(z)\ (dP_r)}{(P_r)}}{1 + \dfrac{(B)\ (z^2)}{(P_r^2)}} = -\frac{(g)\ (M)\ (dL)}{(g_c)\ (R)\ (T)} \quad . \quad . \quad . \quad (8)$$

At this stage of the derivation four variables, z, P_r, T, and L, remain. The number of variables must be reduced to two before Equation 8 can be integrated. It is at this point that various simplifying assumptions such as constant average z, T, or v values have been introduced previously.

The method proposed in this paper also stems from Equation 8. One simplifying assumption is made. The temperature is assumed constant at some average value. If the temperature is linear with depth, the log mean average value of the absolute temperature provides a rigorous solution of the right hand side of Equation 8 upon integration. The effect of the assumption of an average temperature on the left hand side of Equation 8 is extremely small for problems of practical importance. It is believed, therefore, that a constant average temperature may be assumed with little loss in accuracy.

When the temperature is constant, z is a function of P_r only. The variables in Equation 8 are, therefore, separate and both sides of the equation may be integrated. Since z is an empirical function of P_r, the inte-

gration of the left hand side was carried out numerically using the mid-ordinate rule. For this purpose the z chart[3] was reduced to tabular form. Tables and graphs of

$$\int_{(P_r)}^{P_r} \frac{\dfrac{(z)\ (dP_r)}{(P_r)}}{1 + \dfrac{(B)\ (z^2)}{(P_r^2)}} \text{ vs } P_r$$

were then prepared with B and T_r as parameters. The results are shown in Figs. 1 and 2 and in Tables 1, 2, and 3.

Fig. 1 was prepared for the low pressure range of reduced pressures from 1.0 to 5.0, or pressures from about 600 psia to 3,200 psia. Fig. 2 was prepared for the high pressure range of reduced pressures of about 3.0 to 12.0, or pressures above about 2,000 psia. Adequate overlap has been provided so that most problems can be worked entirely on one chart. A reduced temperature range of 1.5 to 1.7 was considered to include most problems of importance. Values of B of from 0 to 20 are plotted on Fig. 1 and values from 0 to 10 are plotted on Fig. 2.

The lower limit of the integral was carefully selected for each chart so as to minimize the spread between lines of constant B and thus simplify interpolation. Interpolation between values of the reduced temperature was at the same time either simplified or eliminated. For Fig. 1 a lower limit of $P_r = 3.0$ was selected. It can be seen that with this lower limit difficulty in interpolation appears only at low reduced pressures. In order to avoid negative values of the integrals on Fig. 1, a constant value of 0.5 was added to all of the integrals. The constant disappears when integrating between two limits.

Bottom-hole pressures are calculated as follows:

1. B is evaluated. A simplified equation for B is

$$B = \frac{(667)\ (f)\ (Q^2)\ (T^2)}{(D')^5 (p_c^2)}$$

2. The right hand integral of Equation 8 is evaluated. A simplified expression for this integral is

$$\frac{(0.01877)\ (G)\ (L)}{(T)}$$

3. The reduced wellhead pressure (p_r) is evaluated.
4. On Fig. 1 or 2 read upward from (p_r) to the proper B and T_r curve and read the value of the integral.
5. Subtract $(0.01877)\ (G)\ (L)/(T)$ from the integral.
6. Read the reduced pressure corresponding to the new value of the integral. This is the reduced bottom-hole pressure (p_r).
7. Calculate the bottom-hole pressure from (p_r).

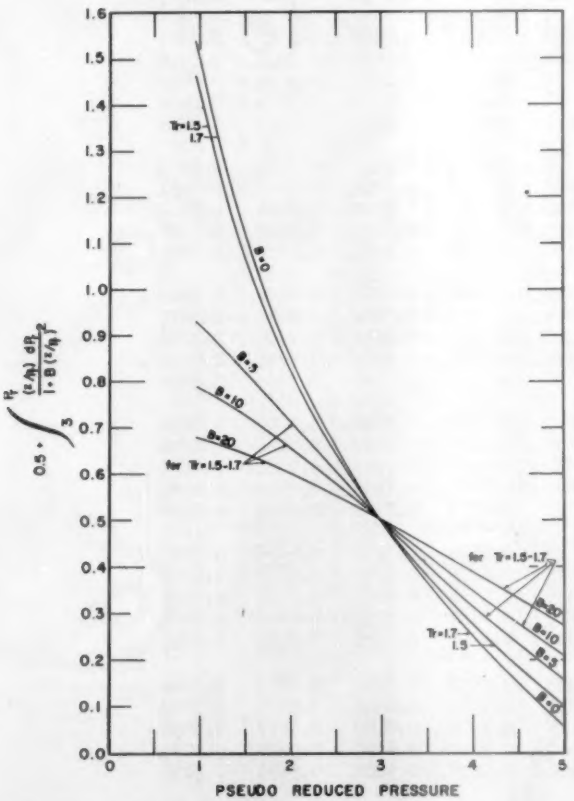

FIG. 1 — CHART FOR THE DIRECT CALCULATION OF BOTTOM HOLE PRESSURES (LOW PRESSURE REGION).

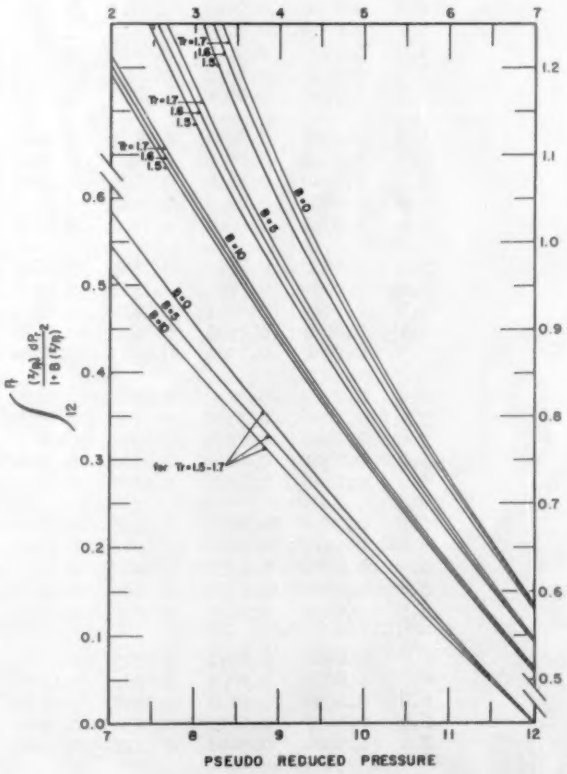

FIG. 2 — CHART FOR THE DIRECT CALCULATION OF BOTTOM HOLE PRESSURES (HIGH PRESSURE REGION).

TABLE 2

Table of $\int_{12}^{P_r} \frac{(z/P_r)\, dP_r}{1 + B(z/P_r)^2}$

	T_r = 1.5			T_r = 1.6			T_r = 1.7		
P_r	B=0	B=5	B=10	B=0	B=5	B=10	B=0	B=5	B=10
2.0	1.5946	1.3471	1.1904	1.6458	1.3708	1.2027	1.6925	1.3926	1.2134
2.1	1.5546	1.3249	1.1751	1.6040	1.3485	1.1875	1.6490	1.3703	1.1983
2.2	1.5167	1.3029	1.1595	1.5643	1.3263	1.1721	1.6077	1.3480	1.1831
2.3	1.4808	1.2811	1.1438	1.5275	1.3042	1.1565	1.5684	1.3258	1.1676
2.4	1.4466	1.2595	1.1281	1.4906	1.2824	1.1408	1.5310	1.3038	1.1521
2.5	1.4140	1.2382	1.1123	1.4562	1.2608	1.1251	1.4951	1.2820	1.1364
2.6	1.3829	1.2173	1.0965	1.4234	1.2395	1.1093	1.4608	1.2604	1.1206
2.7	1.3531	1.1966	1.0807	1.3919	1.2184	1.0935	1.4279	1.2497	1.1048
2.8	1.3246	1.1764	1.0650	1.3616	1.1977	1.0777	1.3963	1.2180	1.0890
2.9	1.2972	1.1564	1.0493	1.3325	1.1772	1.0619	1.3659	1.1972	1.0732
3.0	1.2708	1.1369	1.0338	1.3045	1.1571	1.0462	1.3366	1.1767	1.0575
3.1	1.2453	1.1176	1.0187	1.2775	1.1373	1.0306	1.3082	1.1565	1.0417
3.2	1.2208	1.0988	1.0030	1.2515	1.1179	1.0151	1.2809	1.1366	1.0261
3.3	1.1970	1.0803	0.9878	1.2262	1.0988	0.9997	1.2544	1.1170	1.0105
3.4	1.1740	1.0621	0.9728	1.2018	1.0800	0.9844	1.2288	1.0977	0.9951
3.5	1.1516	1.0442	0.9579	1.1782	1.0615	0.9692	0.2039	1.0787	0.9797
3.6	1.1299	1.0266	0.9431	1.1552	1.0433	0.9542	1.1798	1.0600	0.9645
3.7	1.1087	1.0093	0.9285	1.1329	1.0254	0.9393	1.1563	1.0416	0.9493
3.8	1.0881	0.9923	0.9140	1.1112	1.0078	0.9245	1.1336	1.0235	0.9343
3.9	1.0680	0.9756	0.8997	1.0899	0.9905	0.9099	1.1113	1.0057	0.9194
4.0	1.0484	0.9591	0.8856	1.0692	0.9735	0.8954	1.0897	0.9881	0.9047
4.1	1.0292	0.9429	0.8715	1.0490	0.9567	0.8810	1.0685	0.9708	0.8901
4.2	1.0104	0.9269	0.8576	1.0292	0.9401	0.8668	1.0478	0.9538	0.8756
4.3	0.9920	0.9112	0.8439	1.0099	0.9239	0.8528	1.0276	0.9370	0.8612
4.4	0.9739	0.8957	0.8303	0.9909	0.9078	0.8388	1.0077	0.9204	0.8470
4.5	0.9562	0.8804	0.8168	0.9723	0.8919	0.8250	0.9883	0.9041	0.8239
4.6	0.9388	0.8652	0.8034	0.9541	0.8763	0.8113	0.9693	0.8880	0.8189
4.7	0.9216	0.8503	0.7902	0.9361	0.8608	0.7977	0.9506	0.8721	0.8051
4.8	0.9048	0.8356	0.7770	0.9185	0.8456	0.7843	0.9323	0.8564	0.7914
4.9	0.8882	0.8210	0.7640	0.9012	0.8305	0.7710	0.9143	0.8409	0.7778
5.0	0.8719	0.8066	0.7511	0.8842	0.8156	0.7578	0.8966	0.8256	0.7643
5.1	0.8558	0.7923	0.7384	0.8674	0.8009	0.7447	0.8791	0.8104	0.7509
5.2	0.8400	0.7783	0.7257	0.8508	0.7864	0.7317	0.8620	0.8645	0.7377
5.3	0.8243	0.7643	0.7131	0.8345	0.7720	0.7188	0.8451	0.7797	0.7246
5.4	0.8089	0.7505	0.7007	0.8184	0.7577	0.7060	0.8285	0.7651	0.7115
5.5	0.7936	0.7369	0.6883	0.8026	0.7436	0.6933	0.8120	0.7506	0.6986
5.6	0.7785	0.7233	0.6760	0.7869	0.7297	0.6807	0.7958	0.7363	0.6858
5.7	0.7636	0.7090	0.6638	0.7714	0.7158	0.6683	0.7799	0.7221	0.6730
5.8	0.7488	0.6966	0.6517	0.7561	0.7021	0.6559	0.7641	0.7081	0.6604
5.9	0.7342	0.6834	0.6396	0.7410	0.6886	0.6435	0.7485	0.6942	0.6479
6.0	0.7198	0.6703	0.6277	0.7260	0.6751	0.6313	0.7331	0.6805	0.6354
6.1	0.7055	0.6573	0.6158	0.7112	0.6618	0.6192	0.7179	0.6668	0.6231
6.2	0.6913	0.6445	0.6040	0.6966	0.6486	0.6071	0.7039	0.6533	0.6108
6.3	0.6773	0.6317	0.5923	0.6821	0.6355	0.5952	0.6880	0.6400	0.5986
6.4	0.6634	0.6190	0.5807	0.6678	0.6225	0.5833	0.6733	0.6267	0.5866
6.5	0.6496	0.6065	0.5691	0.6536	0.6096	0.5715	0.6588	0.6135	0.5746
6.6	0.6360	0.5940	0.5576	0.6396	0.5968	0.5597	0.6444	0.6005	0.5626
6.7	0.6224	0.5816	0.5461	0.6257	0.5841	0.5481	0.6301	0.5875	0.5508
6.8	0.6090	0.5692	0.5347	0.6119	0.5715	0.5365	0.6160	0.5747	0.5390
6.9	0.5957	0.5570	0.5234	0.5982	0.5590	0.5250	0.6020	0.5620	0.5273
7.0	0.5824	0.5448	0.5122	0.5847	0.5466	0.5135	0.5882	0.5493	0.5157

TABLE 3

Table of $\int_{12}^{P_r} \frac{(z/P_r)\, dP_r}{1 + B(z/P_r)^2}$

	$T_r = 1.5$			$T_r = 1.6$			$T_r = 1.7$		
P_r	B=0	B=5	B=10	B=0	B=5	B=10	B=0	B=5	B=10
7.0	0.5824	0.5448	0.5122	0.5847	0.5466	0.5135	0.5882	0.5493	0.5157
7.1	0.5693	0.5327	0.5010	0.5712	0.5343	0.5021	0.5745	0.5368	0.5041
7.2	0.5562	0.5207	0.4898	0.5579	0.5221	0.4908	0.5609	0.5243	0.4927
7.3	0.5433	0.5088	0.4787	0.5447	0.5099	0.4796	0.5474	0.5120	0.4811
7.4	0.5304	0.4969	0.4677	0.5315	0.4978	0.4684	0.5340	0.4997	0.4699
7.5	0.5176	0.4851	0.4567	0.5185	0.4858	0.4572	0.5207	0.4875	0.4586
7.6	0.5049	0.4733	0.4457	0.5056	0.4739	0.4461	0.5076	0.4754	0.4474
7.7	0.4923	0.4616	0.4349	0.4928	0.4620	0.4351	0.4945	0.4634	0.4363
7.8	0.4797	0.4500	0.4240	0.4800	0.4503	0.4242	0.4816	0.4514	0.4252
7.9	0.4673	0.4384	0.4132	0.4674	0.4385	0.4133	0.4687	0.4396	0.4141
8.0	0.4549	0.4269	0.4025	0.4548	0.4269	0.4024	0.4560	0.4278	0.4032
8.1	0.4425	0.4155	0.3918	0.4423	0.4153	0.3916	0.4433	0.4161	0.3922
8.2	0.4303	0.4041	0.3811	0.4299	0.4038	0.3809	0.4307	0.4044	0.3814
8.3	0.4181	0.3927	0.3705	0.4176	0.3924	0.3702	0.4182	0.3928	0.3706
8.4	0.4059	0.3814	0.3599	0.4053	0.3810	0.3595	0.4058	0.3813	0.3598
8.5	0.3939	0.3702	0.3494	0.3931	0.3696	0.3489	0.3935	0.3698	0.3491
8.6	0.3818	0.3589	0.3389	0.3810	0.3583	0.3383	0.3812	0.3585	0.3385
8.7	0.3699	0.3478	0.3284	0.3690	0.3491	0.3278	0.3691	0.3471	0.3279
8.8	0.3579	0.3367	0.3180	0.3570	0.3359	0.3173	0.3570	0.3359	0.3173
8.9	0.3461	0.3256	0.3076	0.3451	0.3248	0.3069	0.3450	0.3247	0.3068
9.0	0.3343	0.3146	0.2972	0.3332	0.3137	0.2965	0.3330	0.3135	0.2964
9.1	0.3225	0.3036	0.2869	0.3214	0.3027	0.2862	0.3211	0.3024	0.2860
9.2	0.3108	0.2926	0.2766	0.3097	0.2917	0.2758	0.3093	0.2914	0.2756
9.3	0.2992	0.2817	0.2664	0.2980	0.2808	0.2656	0.2976	0.2804	0.2653
9.4	0.2876	0.2709	0.2561	0.2864	0.2699	0.2553	0.2859	0.2695	0.2550
9.5	0.2760	0.2600	0.2460	0.2748	0.2591	0.2451	0.2743	0.2586	0.2448
9.6	0.2645	0.2492	0.2358	0.2663	0.2483	0.2350	0.2627	0.2477	0.2345
9.7	0.2531	0.2385	0.2257	0.2519	0.2375	0.2248	0.2512	0.2370	0.2244
9.8	0.2417	0.2278	0.2156	0.2405	0.2268	0.2147	0.2397	0.2262	0.2143
9.9	0.2303	0.2171	0.2055	0.2291	0.2162	0.2047	0.2284	0.2155	0.2042
10.0	0.2190	0.2065	0.1955	0.2178	0.2055	0.1947	0.2170	0.2049	0.1941
10.1	0.2077	0.1959	0.1855	0.2065	0.1949	0.1847	0.2057	0.1943	0.1841
10.2	0.1964	0.1853	0.1755	0.1953	0.1844	0.1747	0.1945	0.1837	0.1742
10.3	0.1852	0.1748	0.1655	0.1841	0.1739	0.1648	0.1833	0.1732	0.1642
10.4	0.1741	0.1643	0.1556	0.1730	0.1634	0.1549	0.1722	0.1627	0.1543
10.5	0.1629	0.1538	0.1457	0.1619	0.1529	0.1450	0.1611	0.1523	0.1454
10.6	0.1519	0.1433	0.1358	0.1508	0.1385	0.1351	0.1501	0.1419	0.1346
10.7	0.1408	0.1329	0.1260	0.1398	0.1322	0.1253	0.1391	0.1315	0.1248
10.8	0.1298	0.1225	0.1131	0.1289	0.1218	0.1155	0.1281	0.1212	0.1150
10.9	0.1188	0.1122	0.1063	0.1179	0.1115	0.1058	0.1172	0.1109	0.1053
11.0	0.1078	0.1018	0.0966	0.1070	0.1012	0.0960	0.1064	0.1007	0.0956
11.1	0.0969	0.0915	0.0868	0.0962	0.0910	0.0863	0.0956	0.0904	0.0859
11.2	0.0860	0.0813	0.0771	0.0853	0.0807	0.0766	0.0848	0.0803	0.0762
11.3	0.0752	0.0710	0.0673	0.0746	0.0705	0.0670	0.0741	0.0701	0.0666
11.4	0.0648	0.0608	0.0577	0.0638	0.0604	0.0573	0.0634	0.0600	0.0570
11.5	0.0535	0.0506	0.0480	0.0531	0.0502	0.0477	0.0527	0.0499	0.0474
11.6	0.0428	0.0404	0.0383	0.0424	0.0401	0.0381	0.0421	0.0399	0.0379
11.7	0.0320	0.0303	0.0287	0.0317	0.0301	0.0285	0.0315	0.0298	0.0284
11.8	0.0213	0.0201	0.0191	0.0211	0.0200	0.0190	0.0210	0.0198	0.0189
11.9	0.0106	0.0100	0.0095	0.0105	0.0100	0.0095	0.0104	0.0099	0.0094

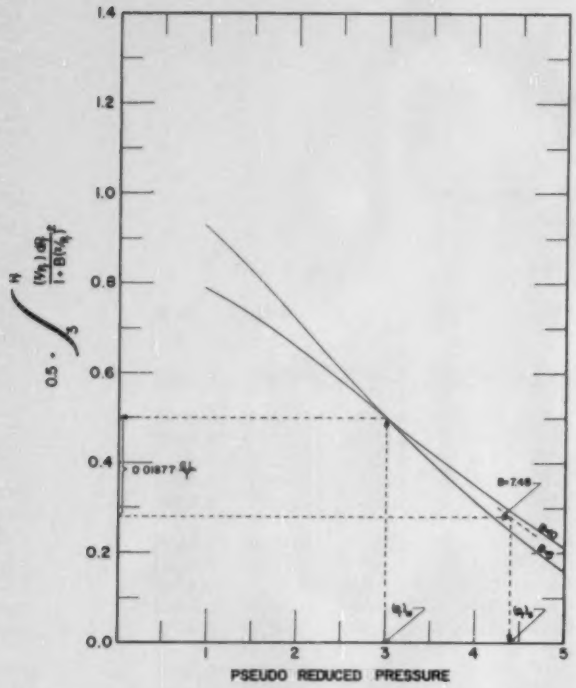

FIG. 3 — EXAMPLE PROBLEM ILLUSTRATING THE USE OF FIGS. 1 AND 2.

ILLUSTRATIVE PROBLEM

The bottom-hole pressure in a flowing gas well is to be calculated.

L = 10,000 ft
D' = 2.00 in
G = 0.750
p_c = 660 psia
T_c = 400° Rankine
p_w = 1,980 psia
Q = 4.91 MMcf/D (at 60°F and 14.65 psia)
f = 0.016
T = 636° Rankine

Solution:

$$B = \frac{(667)\ (0.016)\ (\overline{4.91}^2)\ (\overline{636}^2)}{(\overline{2.00}^5)\ (\overline{660}^2)} = 7.48$$

$$\frac{(0.01877)\ (G)\ (L)}{(T)} = \frac{(0.01877)\ (0.750)\ (10{,}000)}{(636)}$$

$$= 0.2213$$

$$(p_r)_w = \frac{(1{,}930)}{(660)} = 3.00$$

The value of the integral from Fig. 1 is 0.5000. The value of the integral at (p_r) is 0.5000 − 0.2213 = 0.2787. Fig. 3 shows the procedure followed on the integral charts.

$(p_r)_s$ = 4.362

p_s = (4.362) (660) = 2,880 psia

ACKNOWLEDGMENT

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NOMENCLATURE

B = A dimensionless parameter, defined by Equation 7
D = Diameter of the pipe, ft
D' = Diameter of the pipe, in
f = Moody friction factor
G = Gas gravity (Air = 1.0)
g = Acceleration due to gravity, ft/sec²
g_c = Conversion factor, 32.17, (lb-mass) (ft)/(lb-force) (sec²)
L = Length of vertical pipe, ft
M = Molecular weight of gas
P = Pressure, psfa
P_c = Pseudo critical pressure, psfa
P_r = Pseudo reduced pressure, dimensionless
p_s = Bottom-hole pressure, psia
p_c = Pseudo critical pressure, psia
$(p_r)_s$ = Pseudo reduced bottom-hole pressure
$(p_r)_w$ = Pseudo reduced wellhead pressure
p_w = Wellhead pressure, psia
Q = Flow rate MMcf/D (at 60°F and 14.65 psia)
R = Gas constant, 1,545 (ft) (lb-force)/(lb-mole) (°R)
T = Temperature, °R
T_r = Pseudo reduced temperature
v = Velocity, ft/sec
$\bar{V}$ = Specific volume, (ft³)/(lb-mass)
W = Flow rate, lbs/sec
$\bar{w}_s$ = Work done on surroundings, per pound of fluid (ft) (lb-force)/(lb-mass)
$\bar{lw}$ = Work lost due to friction, per pound of fluid (ft) (lb-force)/(lb-mass)
z = Compressibility factor of the gas

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PRESSURE MAINTENANCE by INERT GAS INJECTION in the HIGH RELIEF ELK BASIN FIELD

F. M. STEWART, MEMBER AIME — STANOLIND OIL & GAS CO., TULSA, OKLA.
D. L. GARTHWAITE — CASPER, WYO.
F. K. KREBILL — CODY, WYO.

T.P. 4008

ABSTRACT

Pressure has been maintained in the Elk Basin Tensleep reservoir since the initiation of inert gas injection in Sept., 1949. Oil is being produced under conditions favorable for gravity drainage, including high angle of dip, appreciable structural closure, and fairly good permeability. Results being obtained are high per cent recovery of oil-in-place, sustained field productivity, reduced operating problems, and recovery of plant products. The high recovery has been calculated by application of the gravity drainage theory described in an earlier AIME paper.[1] It is also confirmed from field performance by comparing oil recovery to date with gas cap space voided.

GENERAL INFORMATION

The Elk Basin field lies in Park County, Wyo., and Carbon County, Mont., approximately 50 miles east of Yellowstone Park. Located at the northern end of the Big Horn Basin, the field is situated on an elongated asymmetrical anticline (Fig. 1). The pressure maintenance project covered by this paper involves the Embar-Tensleep reservoir in this multi-pay field. Discovered in Nov., 1942, it has a proved productive area of over 6,300 acres. It consists of the 210-ft thick Tensleep sandstone of Pennsylvanian Age overlain by 40 ft of Embar dolomite of Permian Age. The two formations apparently are in communication with each other and are produced as a common source of supply. As 98 per cent of the reserves are contained in the Tensleep sandstone, in this paper the Embar-Tensleep reservoir will be called simply the Tensleep.

The reservoir is found at an average depth of 4,900 ft, is approximately 7 miles long and 2 miles wide, and has a maximum oil productive closure of 2,330 ft. The strata dip an average of 21° on the west flank and 45° on the east. There are presently 132 Tensleep wells in the field drilled on 40-acre spacing; of these, 17 are shut in because of high gas-oil ratio (GOR) and eight are gas injection wells.

Rock characteristics and related information for the pay section follow:

Porosity, avg	10.7	per cent
Permeability (air) from cores, avg	118	mds
Permeability from PI's	91	mds
Connate water, avg	8	per cent
Initial pressure (–400 ft)	2,234	psia
Pressure April 1954 (–400 ft)	1,327	psia

At high structural positions much of the better sandstone has connate water content of only 2 to 5 per cent as indicated by the coring of wells with oil in nearby Tensleep fields. In special imbibition tests, samples readily imbibed oil but repelled water. In tests on crushed samples, the sand grains rapidly settled in oil and carbon tetrachloride but formed a stable unsinking floc in water. This information indicates that the Tensleep sand is preferentially oil wet.

The oil produced averages 29° API gravity and has a high sulfur content. Extensive sampling and testing have established the fact that characteristics of reservoir oil in this field vary greatly with structure, see Fig. 2. Additional detail on the variation of oil characteristics with structure at Elk Basin may be found in Reference 2. At original reservoir pressure the oil was undersaturated with gas, the bubble point being 1,250 psi at the crest but only 500 psi at the lowest elevation sampled.

As noted on Fig. 2, other fluid properties—reservoir volume factor, solution ratio, gravity, viscosity, and hydrogen sulfide content—likewise vary greatly. These variations complicate mathematical analysis, for it is necessary to average these characteristics in order to enter them into reservoir engineering expressions. To further complicate analysis, sand-face pressure also varies greatly because of the increase in fluid head down structure. As an approximation, average properties under initial conditions may be read from Fig. 2 at the –450-ft elevation.

[1]References given at end of paper.

Manuscript received in Petroleum Branch office on Aug. 30, 1954. Paper presented at Petroleum Branch Fall Meeting in San Antonio, Oct. 17-20, 1954.

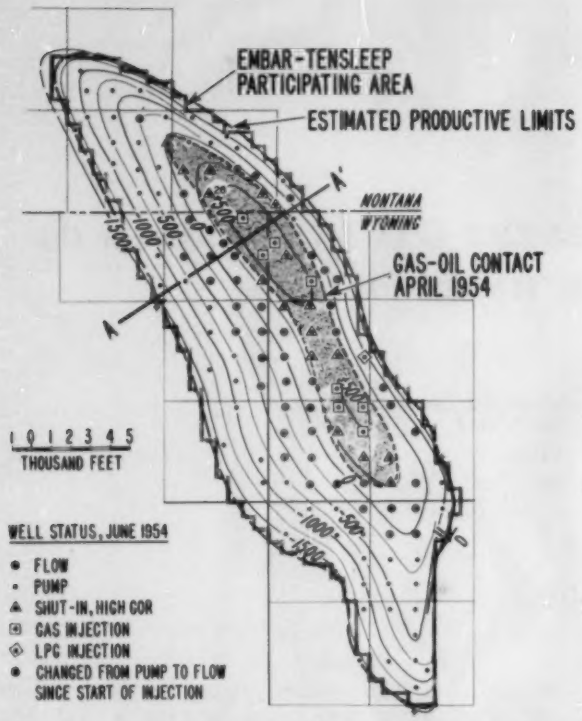

FIG. 1 — STRUCTURE AND WELL STATUS, ELK BASIN TENSLEEP RESERVOIR.

PRIMARY (NON-UNITIZED) HISTORY

Reservoir performance under non-unitized operations is shown on Fig. 3 by the portions of the various graphs prior to May, 1946. Pressure declined rapidly and production was largely by fluid expansion during the initial years while pressure exceeded the bubble point. Although oil on the very apex of the structure was below its original bubble point after July, 1944, released gas had little effect on the pressure curve since the volume of oil so affected was a very small fraction of the total oil-in-place.

Increases in GOR at top-structure wells were noted in early 1945 and a secondary gas cap was recognized. With time, pressure declined below the bubble point as far down structure as –200 ft, but gas released from solution apparently migrated readily up structure since GOR's remained essentially unchanged except at gas cap locations. Field average GOR actually decreased because of the completion of additional down-structure wells producing oil with less gas in solution.

As the Tensleep sandstone is a blanket sand, normally having continuous permeability over large distances, most Tensleep fields have a water drive. Therefore, it was expected that the Elk Basin field would have at least a partial water drive. Analysis by electric analyzer prior to full development of the field indicated some fluid influx, which was assumed to be water. Later on, however, it was found by subsequent development that the fluid which had been migrating into the former productive area was mostly oil. Calculations and pressure data now indicate water influx is negligible.

It was obvious that some gravity drainage would occur under continued non-unitized operation; however, solution gas drive with unrestricted gas production would also occur, resulting in relatively inefficient recovery. Pressure and well productivity under primary operation would decrease comparatively rapidly. Much of the expected recovery would occur at low rates over a very long period of time. Recovery under non-unitized operations was estimated at the time to be 27 per cent of the oil-in-place, being mainly that recoverable by solution drive.

PLANNING AND DEVELOPMENT OF THE PROJECT

After the productive area had been generally outlined, operators made a joint engineering study to ascertain the most efficient method of producing the reservoir. Need for this study was indicated by the apparent lack of sufficient water drive to maintain reservoir pressure and by favorable conditions for gravity drainage, including steep dip, great amount of closure, and good mobility ratio (permeability/viscosity). The formation of a secondary gas cap with low produced GOR's down structure indicated that some gravity segregation was occurring even under competitive operation (Fig. 4).

The study was made before a workable gravity drainage theory, by which recovery could be evaluated, was developed in 1951[3]. However, other projects involving pressure maintenance and gravity drainage under less favorable conditions (less dip, less permeability, and starting at lower pressures) had proved successful in the shallow second Frontier sandstone reservoirs at both Elk Basin and Salt Creek in Wyoming. These projects have been operating since 1926. Recovery of over 42 per cent of oil-in-place is assured from each.

The engineering committee making the study was unable to directly calculate recovery from a unitized crestal gas injection project involving gravity drainage. However, by analogy with the two Frontier projects, they were confident that at least 35 per cent recovery could be obtained. By starting the project early in the life of the field, additional benefits would occur through (1) maintenance of producing capacity and (2) further increase in oil recovery by preventing shrinkage and retaining low oil viscosity.

To take all possible advantage of gravity forces and available reservoir energy, it would be necessary to

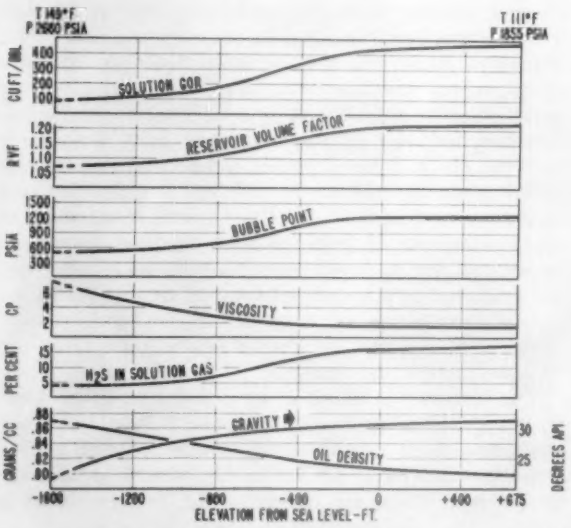

FIG. 2 — RESERVOIR FLUID PROPERTIES AT ORIGINAL CONDITIONS VS ELEVATION, ELK BASIN TENSLEEP RESERVOIR.

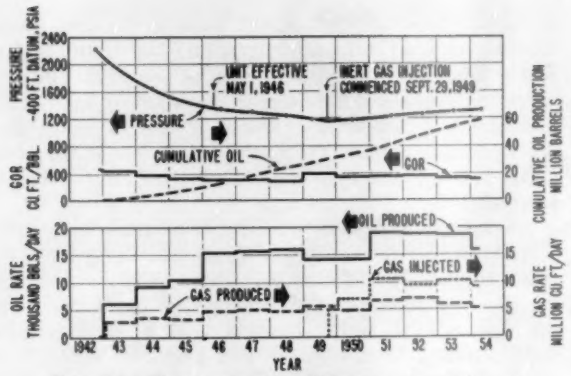

FIG. 3 — PERFORMANCE HISTORY, ELK BASIN TENSLEEP RESERVOIR.

selectively produce the oil from low GOR wells and shut in wells producing appreciable amounts of gas. Such a controlled withdrawal program would require unitization.

As most of the reserves would be produced at solution ratios, future gas production rates would be fairly small. In processing there would be a reduction in gas volume of 24 per cent due to the removal of hydrogen sulfide and carbon dioxide and 13 per cent by removal of liquefiable hydrocarbons. After allowance for plant and lease fuel, plus compressor fuel for injecting sufficient gas to maintain pressure, only about 10 per cent of produced gas would be available for injection. This would be only a small fraction of that needed to maintain pressure. Therefore, the decision was made to generate inert gas, an adequate supply of which could be obtained from plant boiler flue gases. Over nine volumes of inert gas are obtained by burning one volume of hydrocarbon gas.

Unitization became effective in May, 1946. After unitization, the plans for pressure maintenance using inert gas were completed.

PROJECT FOLLOWING UNITIZATION

PERFORMANCE PRIOR TO INJECTION

As soon as unitization became effective, all wells in the gas cap area were shut in and a system of selective production from low GOR wells down structure was established. The effect of unitized operations and selective withdrawals prior to the start of injection operations is evident on Fig. 3. Even though production at this time had reached about 16,000 BOPD, the rate of pressure decline was sharply reduced and field GOR decreased. This can be partly attributed to a larger portion of the reservoir reaching the bubble point in the crestal region. However, the majority of oil-in-place was still at pressures exceeding the bubble point, so that flattening of the pressure curve between 1946 and 1949 was caused primarily by shutting in high GOR wells.

Field operating efficiency was improved by consolidating 46 tank batteries into eight. All pumping units were electrified, power being supplied by the pressure maintenance plant.

PRESSURE MAINTENANCE PLANT

The pressure maintenance plant was designed as an integrated unit to process produced gas, recover liquefiable hydrocarbons, remove hydrogen sulfide and convert it to sulfur, and provide inert gas for pressure maintenance. The inert gas is approximately 90 per cent nitrogen and other inerts and 10 per cent carbon dioxide, with trace amounts of carbon monoxide, sulfur dioxide, nitrogen oxides, and oxygen. It originates as flue gas from a water-tube gas-fired boiler, which is surrounded by a pressure-type casing and is equipped with means for close combustion control and flue gas recirculation.

Control of potential corrosive agents is the critical factor in generating inert gas for injection. No more than .05 per cent oxygen and only trace quantities of water can be tolerated. Excess oxygen is primarily controlled by regulating the air-fuel ratio so that combustibles in the flue gas do not exceed .5 per cent. Secondary control of oxygen is obtained by means of the pressure-type steel casing which prevents air infiltration. Cooled flue gas is recirculated through the casing to maintain approximately 2 in water differential above the fire box pressure. Formation of nitrogen oxides is minimized by lowering flame temperature about 1,000°F by diluting combustion air with flue gas.

Flue gas from the boiler stack is delivered after cooling to the compressor system by means of a turbine-driven blower. By conventional four-stage compression, it is then boosted to 1,500 psi for injection. After the second stage of compression, it is dehydrated so that a dew point of −20°F at 1,500 psi is obtained. In addition, aqua ammonia is injected to maintain the pH of the water removed from the system between 6.5 and 7.0. Through close control of the above corrosion preventive measures, corrosion troubles have been minimized in five years of operation. A more detailed description of inert gas generation facilities at Elk Basin is given in Reference 3.

PERFORMANCE UNDER GAS INJECTION

The plant began processing gas in March, 1949. Injection tests utilizing natural gas were commenced in May, 1949, and full scale injection using inert gas was begun in September of the same year.

Eight injection wells are used, four located on each dome (Fig. 1). While producing 19,000 BOPD, injection of approximately 9,300 Mcf inert gas per day is required to maintain pressure at its present level. For the last three years, injection volumes have averaged 10,200 Mcf/D, which occupies about 26,500 bbl gas cap space. Average daily production during this time has been as follows: 19,000 bbl oil, 5,900 Mcf solution gas, 800 Mcf free gas, and 370 bbl water, or roughly 24,200 reservoir bbl withdrawals. Net injection has exceeded withdrawals by an average of some 2,300 reservoir B/D, or 9.5 per cent.

As a result of injection volumes exceeding with-

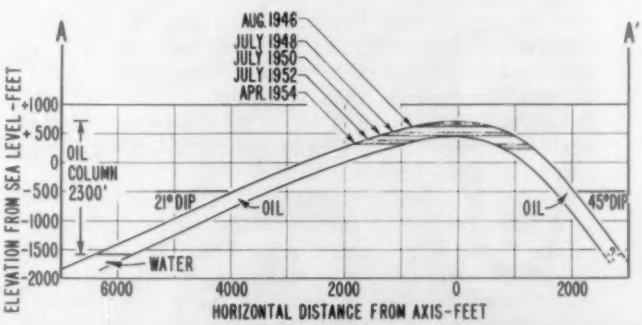

FIG. 4 — CROSS-SECTION SHOWING GAS-OIL CONTACT VS TIME, ELK BASIN TENSLEEP RESERVOIR.

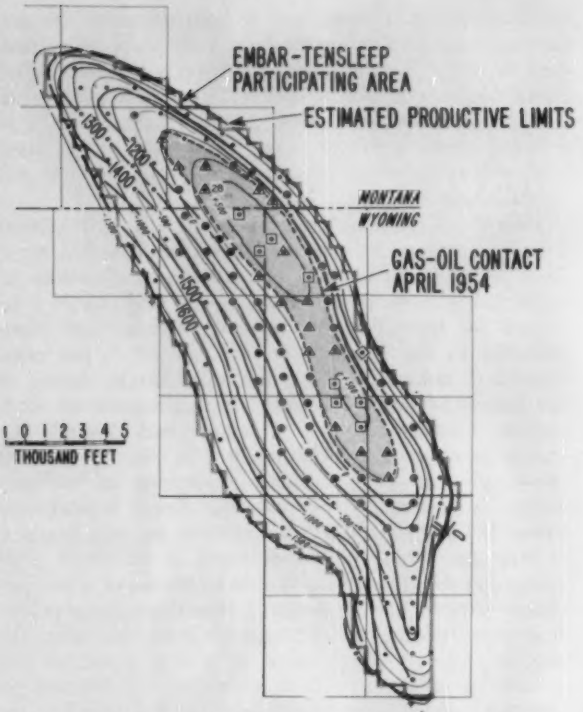

FIG. 5 — SAND-TOP ISOBARS, SUPERIMPOSED ON STRUCTURE MAP, ELK BASIN TENSLEEP RESERVOIR.

drawals during five years of injection, gas cap pressure has been increased 190 psi and average reservoir pressure has been increased 175 psi (Fig. 3). Gas-oil ratio has remained at or near solution ratio. With the increase in pressure, apparently most or all of the gas which had been released down structure and which had not migrated into the gas cap went back into solution.

Position of the gas-oil contact in April, 1954, is shown on Fig. 1. Its movement on the north dome with time is shown on Fig. 4. Its position is confirmed by extrapolating oil gradient up structure and gas gradient down structure from wells on which pressures have been measured below and above the gas-oil contact, respectively. That the gas-oil contact is fairly sharp is evident by the fact that wells go quickly to high GOR once the contact enters the well. Nitrogen content in the gas cap is a good indicator of gas cap gas production. It is determined periodically by Orsat analysis of gas sampled from gas cap and adjacent wells on test. Gas cap gas now averages about 60 per cent nitrogen.

As there are some correlatable tight dolomitic streaks in the Tensleep section, there was some concern initially whether a reasonably uniform gas-oil contact could be maintained. Adequate cross flow between zones is now apparent, occurring either by communication between the more permeable zones or communication through the wells, practically all of which are completed in open hole. Recognizable fingering of gas cap gas down more permeable zones has not occurred.

As evident on the pressure map, Fig. 5, sand-top pressure below the gas-oil contact increases down structure on the flanks in proportion to oil head. This indicates the effectiveness of gravity drainage in replacing produced down-structure oil with oil from higher elevations. However, on the nose areas the increase in sand-top pressure down structure is somewhat less than full oil gradient. For the gas-oil contact to be uniform, oil withdrawn from down-structure wells in the nose areas must be replaced by lateral migration of oil from slightly higher areas in the central portion of the field. This involves only minor differences in elevation or fluid head acting across appreciable lateral distances. Thus, the gravity component of the force moving oil to the nose areas is much less than that moving oil directly down structure.

At times, withdrawals from the nose areas have been such as to permit the fingering of gas along the axis from the gas cap and also the release of some gas from solution. By subsequently decreasing withdrawals from these areas, nose wells at which GOR's had increased have returned to low ratios. For example, Well 28 in April, 1949, had a GOR of 3,000 cu ft/bbl while producing some 50 BOPD. After cutting back production from other wells on the north nose and shutting Well 28 in for several months, tests at low rates indicated the well had returned to solution ratio.

EFFECT OF INJECTION ON RATE

As shown on Fig. 1, 37 producing wells which had to be pumped prior to start of injection are now flowing. Without gas injection, it is estimated that the field would be capable of producing at a rate of 20,000 BOPD until the year 1957. Under unitized pressure maintenance, it is expected that 20,000 BOPD could be maintained for 12 additional years, or through the year 1969. Assuming 20,000 BOPD market demand, 24 million bbl more oil should be produced through 1969 under pressure maintenance than under non-unitized operations. This is an important aspect of the project, but even more impressive is the high ultimate recovery discussed below.

THEORETICAL RECOVERY

The Elk Basin Tensleep reservoir has favorable conditions for gravity drainage. The steep-sided structure with over 2,300 ft of oil-filled closure (Fig. 4) allows the difference in oil and gas density to be effective in moving oil down structure to producing wells. Viscosity of the oil is low enough and permeability high enough that gravity drainage can operate at significant rates. Only a small percentage of the ultimate recovery need be recovered during the stripper stage.

Recoveries from the reservoir have been calculated using the gravity drainage theory described in Reference 1. The two main equations for calculating recoveries, originally presented by Leverett and Buckley[1,5] in 1941 and 1942, are (in conventional units):

$$f_g = \frac{1 - 1.128\dfrac{K_o A}{Q_t \mu_o}\left(\dfrac{\partial P_c \partial S_g}{\partial S_g \partial_u} - g\Delta\rho \sin\alpha\right)}{1 + \dfrac{K_o \mu_g}{K_g \mu_o}} \quad (1)$$

$$\left(\frac{\partial u}{\partial \Theta}\right)_{S_g} = \frac{Q_t}{A\phi}\left(\frac{\partial f_g}{\partial S_g}\right)_{\Theta} \quad (2)$$

f_g = fraction of gas flowing at any point, i.e., (gas flow rate)/(gas flow rate + oil flow rate), all at reservoir conditions
K = effective permeability (Darcys)
A = cross-sectional area of flow path (sq ft)
Q_t = total reservoir flow rate in the u direction (B/D) through area A
viscosity (cp)
P_c = capillary pressure (psi)
S = saturation to a particular phase (fraction)
u = length in the direction of flow (ft)

$g\Delta\rho$ = gravity gradient due to gas and oil density difference (psi/ft)
α = angle of u with horizontal, read minus downward
Θ = time (days)
ϕ = porosity fraction
$_{g,o}$ denote gas and oil, respectively

From the first equation, a curve of f_g vs saturation (Fig. 6) for a particular rate may be computed. Using that and Equation 2, saturation vs height above the gas-oil contact (Fig. 7) can be drawn. From the latter, the average residual saturation and recovery can be calculated.

For reservoirs of high relief, change in capillary pressure with change in gas saturation ($\partial P_c/\partial S_g$) and change in gas saturation with change in distance ($\partial S_g/\partial u$) in Equation 1 need not be calculated. This is true because capillarity has an appreciable effect on recovery over only a limited portion of the gas cap (the so-called stabilized zone in Reference 1). The portion appreciably influenced by capillarity is that immediately adjacent to the gas-oil contact. When this is small relative to the total volume of the gas cap, it may be ignored. At present, the stabilized zone in the Elk Basin Tensleep reservoir is less than 3 per cent of the gas cap volume. It is only 5 to 10 ft out of the total gas cap height of some 440 ft as shown on Fig. 7. As the gas front advances it will become even less important.

Short-Cut Method

For reservoirs of high relief, a short-cut method of estimating recovery is available. This is based on the work of Welge[6] which showed that average gas saturation at gas breakthrough, $\overline{S_g}$, may be calculated directly from the slope of the f_g vs S_g curve at its point of tangency with a straight line drawn from the origin, as follows:

$$\overline{S_g} = S_{g_2} + \frac{1 - f_g}{\left(\frac{f_g}{S_g}\right)_2} \quad \ldots\ldots\ldots \quad (3)$$

Subscript $_2$ denotes the point of tangency.

In practice, Equation 3 need not be used because $\overline{S_g}$ may be read directly at the point found by extending the tangent to its intersection with the $f_g = 1.0$ line.[7] The proof is indicated on Fig. 6 by means of similar triangles above and below the point of tangency as indicated by the shaded areas.

By use of this short-cut, the fractional flow equation with the capillary pressure term deleted (see Appendix) is adequate for estimating recovery. It is not necessary to measure the slopes of any lines as required in the regular procedure. This reduces the amount of work involved in the estimation substantially and eliminates a source of error. It may be used any time the total system is long compared to the length of the stabilized zone. The significance of the stabilized zone can be judged from the length of the transition zone on the air-oil capillary pressure curve (converted to feet of height). However, by itself this is not a sure criterion because the length of the stabilized zone is influenced by other factors, such as rate and permeability.

Recovery To Date

An example of the short-cut method is given in the Appendix and Fig. 6. In the example, recovery from the gas cap area is computed as of April, 1954, using appropriate values for the variables and the average field producing rate of 19,000 BOPD. Average gas saturation at breakthrough, $\overline{S_g}$, for the current oil producing rate is .59. Dividing by .92, the initial oil saturation, a figure of 64 per cent is obtained for the *recovery realized to date* from the area already depleted. Fig. 7 has been added to show the corresponding saturation distribution vs height.

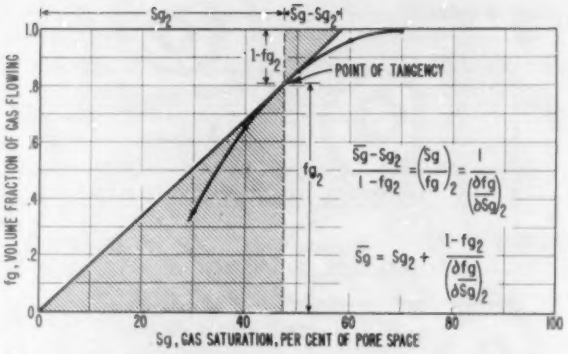

FIG. 6 — FRACTIONAL FLOW OF GAS VS SATURATION FOR 19,000 BOPD RATE WITH GAS-OIL CONTACT AT +237 FT $\left(\frac{Q_t}{A} = 1.66 \text{ B/D/ACRE OF G/O CONTACT.}\right)$

By making a series of calculations for different producing rates and holding all variables except rate constant, a curve like one of those in Fig. 8 results. Fig. 8 shows how theoretical recovery is influenced by the variables in the fractional flow Equation 1. Variables were changed to extreme limits expected and recoveries calculated using these extreme values. This graph clearly shows the importance of permeability, angle of dip, and viscosity on recovery by gravity drainage at Elk Basin.

Ultimate Recovery

Assuming a lower producing rate prior to gas breakthrough at the lowest row of wells, Fig. 8 indicates that *ultimate recovery* from formation of more than 12 md may exceed the 64 per cent calculated for recovery to date. However, ultimate recovery from Tensleep formation of less than 12 md should theoretically be lower than that shown by Curve 9, other variables the same; but laboratory data were not available to investigate this range. On the other hand, there may be cross flow into the more permeable strata which would tend to permit high recovery from the low permeability rock. The check between theoretical recovery and that determined from field performance (see a later section), and the fairly uniform movement of the gas-oil contact, may be interpreted as evidence that such cross flow is occurring. Some 16 per cent of the initial oil-in-place is in formation of less than 12 md permeability.

Calculated recoveries may apply down to the lowest ring of producing wells, a number of which are yet to be drilled. Below that elevation, the position of producing wells will not allow gravity drainage to be very effective. Oil on the very perimeter of the field will be recovered during and after blowdown and will be influenced by solution gas drive.

An outstanding feature of the theoretical analysis is that, regardless of intermediate rates, ultimate recovery for the reservoir should correspond to the producing rate at time of gas breakthrough to the lowest ring of wells. This is because saturation distribution should

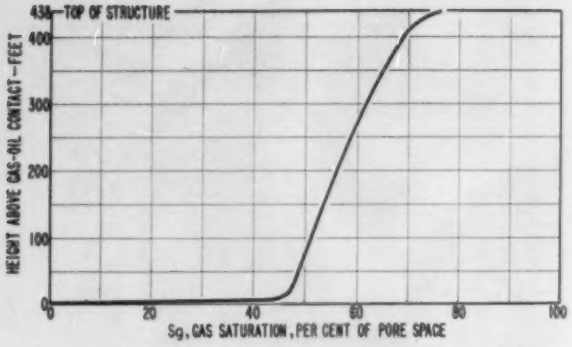

FIG. 7 — SATURATION DISTRIBUTION VS HEIGHT FOR 19,000 BOPD RATE WITH GAS-OIL CONTACT AT + 237 FT.

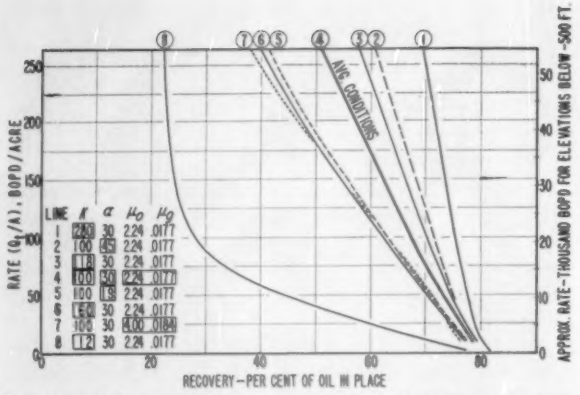
RATE (Q_t/A), BOPD/ACRE
APPROX. RATE—THOUSAND BOPD FOR ELEVATIONS BELOW −500 FT.
RECOVERY—PER CENT OF OIL IN PLACE
AVE. CONDITIONS
LINE k α μ_o μ_g
1 280 30 2.24 .0177
2 100 45 2.24 .0177
3 118 30 2.24 .0177
4 100 30 2.24 .0177
5 100 15 2.24 .0177
6 150 30 2.24 .0177
7 100 30 4.00 .0184
8 112 30 2.24 .0177

FIG. 8—CALCULATED EFFECT OF RATE, PERMEABILITY, DIP, AND VISCOSITY ON RECOVERY, ELK BASIN TENSLEEP RESERVOIR.

readjust rapidly after change of rates as indicated by research experiments with packed sand columns. However, the statement holds only if all wells are shut in immediately upon gas breakthrough; and this contingency plus well capacity may limit the practical current producing rate to some extent. Readjustment of saturation distribution with decreasing rate results in higher recovery as indicated on Fig. 8.

FACTORS IN THEORETICAL CALCULATION

Theoretical recovery, both ultimate and that obtained from the area depleted to date, is of course subject to qualification. The main problem in applying the method at Elk Basin is to choose proper values for the factors in Equation 1. From detailed log and core study, it was concluded that sufficient homogeneity exists to permit use of average values for all factors. Thus, calculation by sections was eliminated, keeping computations down to practical limits.

With pressure being maintained, Q_t, which represents net fluid flow from the gas cap, was assumed to be the oil producing rate converted to reservoir conditions. The values of Q_t were arbitrarily chosen between 500 and 50,000 BOPD to cover any foreseeable future producing rate. This permitted a complete evaluation of the effect of rate on recovery, although it will not be physically possible to produce at the higher rates continuously to abandonment.

The cross-sectional area at the gas-oil contact perpendicular to flow, A, is considered to be constant in the theoretical derivation. However, in actuality the area may vary with time due to the shape of the reservoir. In estimating recovery, the area used is that existing at the gas-oil contact corresponding to the stage of depletion studied.

The permeability to oil, K_o, was taken as an average for the entire reservoir. For the condition of no gas saturation, it was calculated from PI data obtained when the producing bottom-hole pressure was above the bubble point. Relative permeability characteristics were taken from laboratory flow tests. For the several samples tested, there was fairly close agreement in both the K_o/K and K_o/K_g relationships so that an average graph of test results could be used.

The value used for viscosity was a weighted average since viscosity varies with structural elevation. Averaging was also necessary to account for change in gas-oil contact and for the natural mixing which takes place as oil migrates down structure. No allowance for viscosity change due to pressure variation was made because most of the oil will be above its bubble point for a major portion of the reservoir's life.

The factor $g\Delta\rho$ was computed from the difference in density of reservoir oil and gas cap gas. Weighted averages were used because of the variation in density with structural elevation.

The value α was taken as the average dip angle. Dip on the east flank is considerably different from that on the west and on the noses. Recovery could be calculated separately for each flank, and this was actually done; however, an average dip angle was determined later which would give approximately the same answer. Recovery from the nose areas, where dip changes rapidly and flattens, is expected to be somewhat less than that from the flanks.

In calcuating theoretical recovery, complete maintenance of pressure has been assumed to depletion. Some shrinkage of oil-in-place should occur eventually as a result of (1) a drop in pressure after termination of injection and (2) the effect of injected nitrogen in reducing the solubility of hydrocarbon gas in crude oil. Such shrinkage and its effect on oil viscosity would cause recovery from the lower portion of the reservoir to be less than that otherwise anticipated.

RECOVERY FROM FIELD PERFORMANCE

Recoveries as calculated by the gravity drainage theory may be checked by field performance using the "net vacated space" method. All reservoir space formerly occupied by oil but now occupied by free gas is compared with the total hydrocarbon pore volume of the gas cap. This represents recovery if essentially all free gas remaining in the reservoir is in the gas cap. This is believed true because (1) wells immediately below the gas cap produce at low GOR's, (2) pressure has increased sufficiently to have caused any free gas existing down structure to go back into solution, and (3) equilibrium gas saturation according to laboratory flow tests is less than 1 per cent.

Net reservoir space vacated is evaluated as follows:

$$G = n\beta_o + (N - n)\ (\beta_o - \beta) + w - L$$

G = net reservoir space vacated and now occupied by free gas
N = original stock tank oil-in-place
n = cumulative stock tank oil produced
β_o = original reservoir volume factor for oil
β = reservoir volume factor for oil after producing n barrels

w = cumulative water production
L = cumulative liquid injected plus water influx

Net water encroachment into the reservoir is taken to be zero. To April, 1954, some 300,000 bbl of surplus butane and propane have been injected near the gas-oil contact.

Total field oil-in-place was calculated by the material balance method. However, in order to do this it was first necessary to get average oil properties by weighting for oil-in-place vs contour intervals as determined from pore-volume calculation. Then, by finding a porosity cut-off which would make the pore-volume estimate of oil-in-place agree with that determined from the material balance, it was possible to obtain an applicable curve of pore volume vs elevation. If the elevation of the gas-oil contact at a particular time be known, the corresponding gas cap pore volume could then be read.

Recovery as of April, 1954, determined by this method is as follows:

Net Space Vacated by Liquid	Hydrocarbon Pore Volume Above Gas-Oil Contact	Per Cent Recovery
69,100,000 bbl	105,500,000 bbl	66

The 66 per cent figure is reasonably close to the 64 per cent calculated by the theoretical method. The accuracy of the calculation of recovery from field performance depends on the accuracy with which the gas-oil contact and the pore volume above this contact may be determined. It also depends on the validity of the premise that there is negligible water influx and only minor amounts of free gas below the gas-oil contact. Therefore, recovery determined from field performance so far must also be qualified and may not apply precisely to recovery from the undepleted section. However, the method becomes more reliable with time because error in determining gas cap volume is less significant as the gas cap becomes larger.

SUMMARY

1. For the portion of the Elk Basin Tensleep reservoir depleted to date, there is reasonably close agreement between theoretical recovery (64 per cent) and that calculated from field performance (66 per cent).

2. In spite of the qualifications required, there is ample reason to believe that the theoretical calculations can be adapted with experience to reliably predict recovery by gravity drainage with pressure maintenance under conditions such as those existing at Elk Basin.

3. The Elk Basin Tensleep unitized operation, utilizing gravity drainage and inert crestal gas injection, is a model of modern conservation practice. As confirmed by field performance, the secondary recovery program is resulting in very efficient recovery of oil-in-place, exceeding original expectations. Economic success is further assured by sustained field producing capacity, reduced operating problems, and recovery of plant products.

ACKNOWLEDGMENT

The writers thank the management of Stanolind Oil and Gas Co. for permission to prepare and present this paper.

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APPENDIX

Example — Calculation of theoretical recovery for 19,000 BOPD rate from Elk Basin Tensleep Reservoir, gas-oil contact at +237 ft.

Step 1. Compute values of f_g corresponding to different values of S_g assumed; plot graphically (Fig. 6).

Equation: $$f_g = 1 - \frac{1.128 \dfrac{K_o A}{Q_t \mu_o} \left(-g\Delta\rho \sin\alpha\right)}{1 + \dfrac{K_o}{K_g}\dfrac{\mu_g}{\mu_o}}$$

(1) S_g	(2) K_o	(3) $-1.128 \frac{K_o}{\mu_o} g\Delta\rho \sin\alpha$	(4) Col. 3 $\times Q_t/A$	(5) 1-Col. 4	(6) $\frac{K_o}{K_g}$	(7) $1 + \frac{K_o}{K_g}\frac{\mu_g}{\mu_o}$	(8) f_g Col. 5 / Col. 7
.80	.0000	.000	.000	1.000	.000	1.000	1.000
.70	.0001	.016 x 10^{-6}	.002	.998	.003	1.000	.998
.60	.0019	.309 "	.041	.959	.077	1.001	.958
.50	.0067	1.09 "	.144	.856	.589	1.005	.852
.40	.0155	2.52 "	.332	.668	2.38	1.019	.656
.30	.0298	4.71 "	.639	.361	7.15	1.057	.342

S_g, assume values downward until tangent can be drawn to f_g vs S_g curve as on Fig. 6.

$K_o = K_o/K$ (from laboratory data) times .091 Darcy.

μ_o = 2.24 cp, from bottom hole sample analysis.

$g\Delta\rho$ = oil gradient of .351 psi/ft minus the gas gradient of .026 psi/ft.

α = 30°, average dip for both flanks.

Q_t/A = .00382 B/D/sq ft, (166 B/D/acre) = rate of production, 19,000 BOPD, converted to reservoir conditions using RVF of 1.161, divided by flow path area, 5.78 × 10^6 sq ft, at the gas-oil contact.

$\frac{K_o}{K_g}$, relative permeability data from laboratory flow tests.

μ_g = .0177 cp, calculated by the method of Bicher and Katz.[8]

Step 2. Draw tangent to f_g vs S_g curve starting from origin and intersecting the line $f_g = 1.0$. The value of S_g at this point of intersection closely represents the average residual gas saturation; the value as read from Fig. 6 is .59.

Step 3. Fractional recovery = S_g/(1-connate water saturation) = .59/.92 = .64. ★★★

DISCUSSION

LINCOLN F. ELKINS
MEMBER AIME

SOHIO PETROLEUM CO.
OKLAHOMA CITY, OKLA.

Petroleum literature contains only a few examples of performance of gravity drainage reservoirs and these are limited primarily to end results with only partial analysis of intermediate drainage rates and recovery efficiencies. A few years ago co-workers of the authors developed a workable theory of gravity drainage which agreed closely with laboratory experiments, and the authors have extended its use to check the past performance and to predict future performance of this important reservoir. Together these represent a notable step forward in petroleum reservoir engineering. Their efforts and the permission for early publication of these results granted by their employer are gratefully appreciated.

Beyond the concise description of the Elk Basin Tensleep reservoir, its performance under primary operation, and the results of the unique flue gas injection pressure maintenance program, the main thesis of the paper is the almost identical agreement between past recovery efficiency calculated from field performance (66 per cent) and that calculated from gravity drainage theory (64 per cent) for that portion of the reservoir above the gas-oil contact. Such high average recovery efficiency so early in the performance of the reservoir and such excellent agreement between theory and practice are surprising, particularly when the Tensleep is not one uniform continuous sand section but consists of many sand members of varying permeability separated by correlatable tight dolomitic streaks. No correction for effects of variable permeability profile is indicated in the theoretical calculations in the paper. Therefore it is appropriate to consider the range of uncertainty in recovery efficiency calculated from field performance due to the authors' two basic assumptions of no significant water influx and only minor amounts of free gas saturation below the gas-oil contact used in the analysis.

The electric analyzer study of water influx into this reservoir mentioned in the paper had available that portion of the pressure-production period from 1942-44 when the entire reservoir was above the saturation pressure so complications due to variable saturation pressure, varying actual pressures at different structural positions, etc., did not arise. Analyzer prediction of water influx using the actual pressure history that has since occurred at Elk Basin totals some 12 million bbl to date, at least half of which would have occurred while there was a column of about 300 ft between the lowest known oil point tested in wells and the top of the sand in the dry hole at the west boundary of the unit area. The total calculated water influx is less than 2 per cent of the reservoir volume and it would cause a rise in oil-water contact of just 70 ft at 50 per cent displacement efficiency. The water level established by more recent drilling is approximately this far above the dry hole drilled before unitization. This amount of water influx would reduce the calculated recovery efficiency from 66 per cent to 54 per cent for that portion of the reservoir above the gas-oil contact.

By May, 1945, the reservoir at Elk Basin had declined about 700 psi below the initial pressure. At that time the discovery Tensleep well was completed in the South Elk Basin field located about 2 miles southwest of the limits of Elk Basin. The pressure there was about 400 psi lower than the Elk Basin pressure initially after proper correction for the oil and water columns between the two datum levels. Although not actual proof, this certainly is presumptive evidence of some significant water influx.

Prior to gas injection actual reservoir pressure had declined to the saturation pressure as low as the −200 ft level, whereas the present gas-oil contact is in the vicinity of +200 ft to +300 ft. For these conditions it is estimated that some 5 billion cu ft of gas was released from solution and at the reservoir conditions this would occupy some 12 million bbl space equivalent to about 6 per cent average gas saturation. Certainly some of this has migrated up-structure and some of it has been redissolved in oil during the period of increasing pressure, but the actual quantities are indeterminate.

In another smaller reservoir having similar dip but higher core permeability and much lower oil viscosity than Elk Basin, reservoir pressure was reduced hundreds of psi below the saturation pressure before there was a significant increase in gas-oil ratio of wells in mid-flank positions. Two new wells some 400 ft to 700 ft higher than the mid-flank wells and very near the top of the structure were completed shortly after gas-oil ratios began to increase in the mid-flank wells. Gas-oil ratios of the new wells were comparable to those of the older wells. If no free gas had migrated updip, the gas saturation in the vicinity of these mid-flank wells would have been of the order of 12 per cent. If all the gas had migrated updip the resulting gas cap should have encompassed the new wells, which is contrary to their gas-oil ratio performance initially. Thus it appears gas saturations of quite a few per cent can be achieved in some cases before sufficient effective permeability to gas develops to permit significant flow of gas updip.

Combining electric analyzer prediction of 12 million bbl of water influx and possible free gas saturation up to 12 million bbl below the gas-oil contact would reduce the calculated oil recovery efficiency to 42 per cent for the region above the gas-oil contact. The actual value is probably somewhere between this 42 per cent and 66 per cent calculated neglecting water influx and any free gas below the gas-oil contact if all other reservoir factors are correct. Even 42 per cent oil recovery efficiency so early in the field life is an example of excellent reservoir performance.

Since to me there is some doubt that the actual oil recovery efficiency has so closely approached the theoretical calculations with no correction for variations in permeability between the various separate members of the Tensleep Sand, I should like to ask the authors two questions:

1. What method of material balance calculation was made to properly account for the widely varying fluid properties and saturation pressures, and varying amounts of oil which were below the saturation pressure such that calculations and pressure data indicate water influx has been negligible?

2. Have there been any selective recompletion tests of wells in the gas cap region which confirm a high oil recovery efficiency in each sand section of the Tensleep? ★★★

AUTHORS' REPLY TO LINCOLN F. ELKINS

As stated in the paper, the accuracy of recovery calculated from field performance depends largely on (a) the determination of pore volume above the gas-oil contact and (b) the validity of the basic premises that there is negligible water influx and only minor amounts of free gas below the gas-oil contact. Lincoln F. Elkins attempts to find the range of uncertainty in calculated recovery considering maximum error which could occur in the premises (b).

WATER INFLUX

Three things substantiate the statement that water influx is negligible: (1) material balance calculations, (2) direction of datum-pressure gradient, and (3) WOR history on individual wells.

At the time the analyzer study was made, the field was only partially developed and pressure data were from wells above the minus 500-ft contour. The study showed several thousand barrels per day fluid coming into the developed area. Datum pressures increased generally toward the boundary of the developed area, this being considered proof of water influx. After further development down-structure, however, the direction of the pressure gradient became reversed, pressure consistently decreasing toward the edge. From that time to start of injection, material balance calculation with time, assuming no water influx, gave reasonably consistent values for oil-in-place. No increasing trend in calculated oil-in-place was observed. These data support the assumption of negligible influx. Obviously, fluid had been moving into the developed area at the time of the analyzer study, but apparently that fluid was mostly oil from the undeveloped portion.

Further substantiation of negligible influx is the WOR history on individual wells. Per cent water has gradually decreased at nine wells, four have produced a consistently small per cent, and only two have shown an increase. As an example, at one well per cent water decreased gradually over a four years' period from 75 to 26.

In answer to Elkins' first question, average oil properties weighted according to oil-in-place by horizontal segments were used in the material balance. Allowance was made for the effect of down-structure migration on oil properties. The properties at the time of a particular survey were taken as those for the elevation from which the oil had migrated but at the pressure of the segment it then occupied.

Cumulative influx cannot be precisely evaluated. Certainly some has occurred, but it is believed to be a relatively small amount, undoubtedly much less than the 12 million bbl mentioned by Elkins as a maximum.

FREE GAS SATURATION

The amount of free gas saturation which exists between -200 ft and the present gas-oil contact is less certain. The paper listed three things substantiating the contention that minor amounts of free gas exist below the gas-oil contact. To amplify on these, at sea level elevation initial bubble point was 1,205 psi, lowest pressure reached was 1,060 psi, and pressure in April, 1954, was 1,235 psi. Since the latter is greater than initial bubble point, gas released below this elevation should have gone back into the solution. At $+$ 100 ft, initial bubble point was 1,230, lowest pressure reached was 1,025, and April, 1954, pressure was 1,200 psi. This is only 30 psi below the initial bubble point for this elevation; and, the pressure increase is sufficient to have put several per cent gas saturation back into solution. Regardless of the exact value of equilibrium gas saturation, it is apparent that there should be little free gas currently existing on the flanks below the gas-oil contact in view of the increase in pressure which has occurred. By inspection of Fig. 5, however, it is reasonable to believe that some gas saturation likely exists on the noses below the contact.

The authors do not wish to give the impression that recovery determined from field performance to date is known exactly. Limitations on the method must be recognized; however, the basic premises used are believed justified even though both would tend to make calculated recovery too high. The authors believe that the range of uncertainty discussed by Elkins is much too broad; i.e., recovery obtained is much closer to 66 than 42 per cent.

In answer to Elkins' second question there have not been any selective recompletion tests of wells in the gas cap region. ★★★

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